Sedimentological and Petrophysical Properties of Sandstone Facies belonging to Lambir Formation at Tusan Beach, Miri, Sarawak.

by

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14152

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Technology (Hons)
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CERTIFICATION OF APPROVAL

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PETROLEUM GEOSCIENCE

Approved by,

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May 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(NGUYEN HOANG VIET)

ABSTRACT

Understanding the sedimentological and petrophysical properties (porosity, permeability, density) of Early to Late Miocene Lambir Formation in Miri, Sarawak is essential for the reservoir characterization process of this formation's equivalent located at offshore West Baram Delta. This project focuses on investigating a part of Lambir Formation, which is exposed in Tusan Beach area, along Miri - Bintulu coastline. The lithofacies of Lambir Formation in Tusan Beach area are originated from tidal influenced shallow marine environment, which could possibly make up good hydrocarbon reservoir. Sedimentary features related to shallow marine deposition such as ripple marks, cross beddings, and burrows are commonly seen in this formation. Two outcrops were observed and logged in order to investigate the facies characteristics and petrophysical properties of sandstones belong to Lambir Formation in the study area. In total five sandstone facies had been identified: **i)** Massive sandstone; **ii)** Trough cross-bedded sandstone; **iii)** Herringbone cross-bedded sandstone; **iv)** Tabular cross-bedded sandstone; **v)** Hummocky cross-bedded sandstone. Poro-perm results show high to very high permeability (1105mD to 3018mD) and very good porosity (25.3% to 28.7%) values in all samples, indicating excellent reservoir quality. Generally, samples belong to trough cross-bedded sandstone facies (sample 1, 5, and 6) recorded highest porosity and permeability values, followed by hummocky cross-bedded sandstones (sample 3 and 4) and lastly, herringbone cross-bedded sandstone (sample 2). Less mud content and coarser grain size in trough cross-bedded samples had contributed to this result. Observations also suggest that horizontal permeability is generally higher than vertical permeability of the same facies. High permeability anisotropy is observed in trough cross-bedded and hummocky cross-bedded sandstone facies, reflected through low kV/kH ratios, ranging from 0.42 to 0.55. Permeability distribution of onshore samples can be used as a proxy to predict the permeability trend of this formation offshore.

Key words: Lambir Formation, sandstone facies, petrophysical properties.

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CHAPTER 1

INTRODUCTION

1.1. BACKGROUND OF STUDY

Petroleum production in North East Borneo has been going on since the first oil discovery in Miri area, Sarawak in 1910 (Sorkhabi, 2010). There have been numbers of explorations and productions on the Neogene rocks that are widely distributed in offshore Sarawak (Mazlan, 1999). Currently, the main issue in exploration is the complexity of the distribution, compartmentalization, and architecture of the reservoirs. Fortunately, many of these rock formations are cropped at the onshore part of Sarawak. This provides good opportunities to study and evaluate the sedimentological and reservoir properties of them in order to understand the architecture of these reservoirs at offshore.

In order to qualify a potential reservoir rock, assessment of petrophysical properties such as density, porosity and permeability is necessary. These parameters are controlled by a lot of factors. Different lithology will display significantly different values petrophysical properties. This does not mean that one rock type can be defined by a finite set of these properties. Instead, these properties vary based on types of sedimentological facies as well as diagenesis process that the rock undergoes. Porosity and permeability of a reservoir rock are mainly dependent on lithofacies which is identified on the basis of lithology, texture, grain type, grain size, sedimentary structures, porosity type, type and degree of bioturbation. Petrophysical analysis and lithofacies interpretation can be combined to determine the relationship between these two factors.

This project focuses on investigating the lithofacies and reservoir properties of the sandstone facies of Lambir Formation in Miri, Sarawak. The output of this project if carried out in a larger scope can act as a proxy for the distribution of reservoir properties and other sedimentological features of Lambir Formation offshore, which is an important factor in reservoir characterization. Lambir Formation (Mid – Late Miocene) is mainly located in Lambir Hills area ($4^0$20’ N, 114^{0}E), 30km towards Southwest of Miri, Sarawak. The formation can also be found at Tusan Beach, along the coast line from Miri to Bintulu. Lambir Formation is bounded by Setap Shale Formation to the Southeast and Tukau Formation to the Northwest (Figure 1).

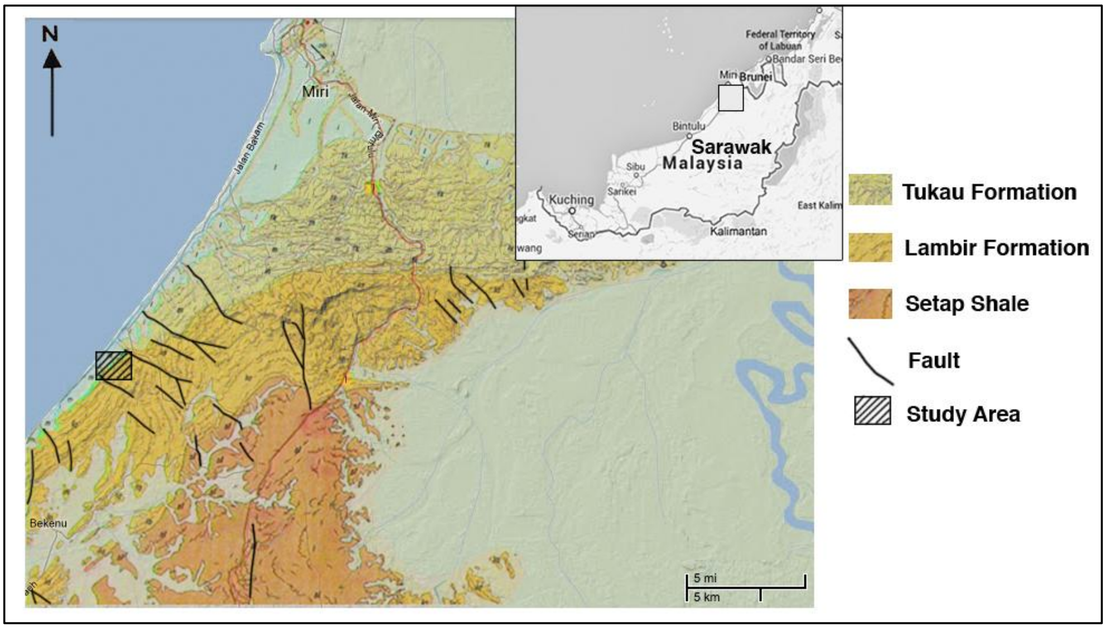

Figure 1: Map of Lambir Hills area, Miri, Sarawak, showing study area (Modified after Kessler & Jong).

1.2. PROBLEM STATEMENT

Lambir Formation (Lower – Upper Miocene) is one of the few formations encountered in Miri area (see figure 2). Other rock formations such as Belait Formation (Mid – Upper Miocene), Tukau Formation (Upper Miocene – Lower Pliocene) and Miri Formation (Mid Miocene) have been discussed in many publications (Mazlan, 1999; Tan, et al., 1999; Teoh & Hadi, 2009). There are numbers of studies and geological surveys carried on Lambir Formation's stratigraphy and sedimentological features. Boren, et al. (1996) introduced a brief summary of field observations on the outcrops in Brunei whereas Simmons, et al. (1999) focused more on biostratigraphy and depositional successions. Recently, Hutchinson (2005) came up with a general overview of the formation, which includes paleoenvironment, fossils found, and sandstone facies. Furthermore, hydrocarbon migration within Lambir Formation has also been studied and proved from numbers of geochemical experiments by Mohd Syamim and Padmanabhan (2011). However, the reservoir pertrophysical properties (porosity, permeability, density) of sandstones in this formation have not been put under considerations. Therefore, this project aims to study the sedimentological as well as petrophysical characteristic of sandstones from Lambir Formation. From which, the effects of depositional environment on reservoir properties can be determined.

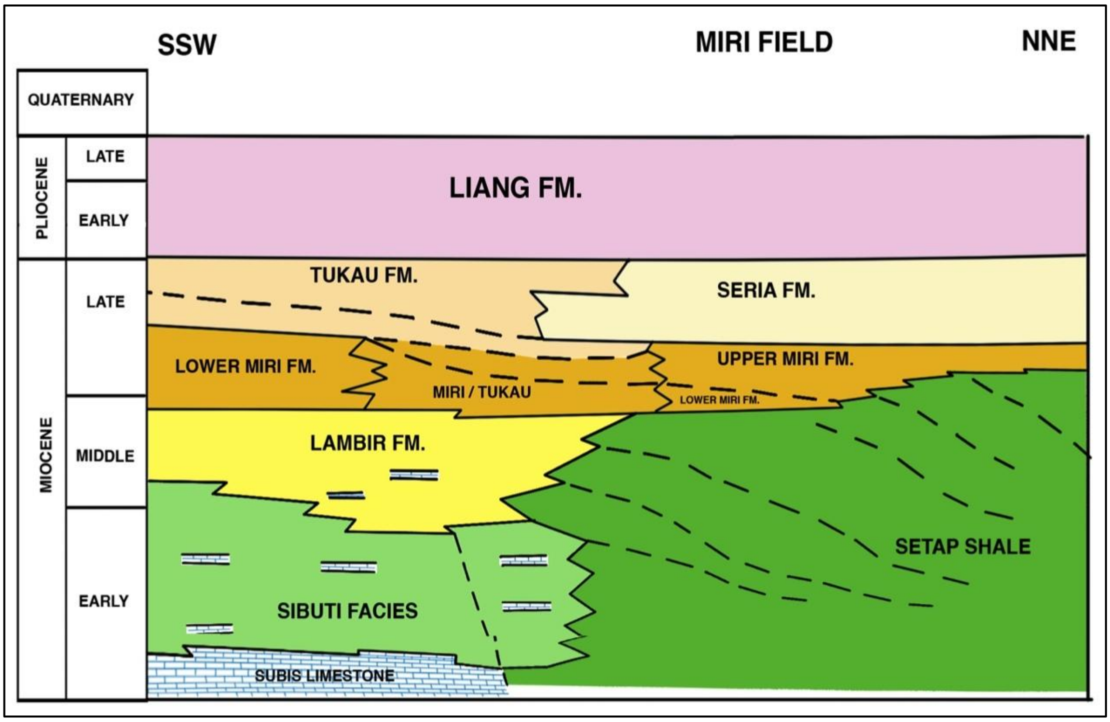

Figure 2 - Schematic Stratigraphy of Neogene formations, Miri, Sarawak. (Modified after Tan, et al., 1999)

1.3. OBJECTIVES OF STUDY

With a clear identification of the problems, the four main objectives of this study are stated below:

- To produce a map for the transect area.
- To identify different sandstone facies of Lambir Formation based on sedimentological characteristics.
- To determine reservoir petrophysical properties of the sandstones belonging to Lambir Formation.
- To establish the relationship between sedimentological and reservoir properties of sandstones in Lambir Formation.

1.4. SCOPE OF STUDY

On the basis of previous published researches, this study focuses on analyzing different lithofacies of a part of Lambir Formation, as well as their reservoir qualities. Hence, this research is divided into two stages. First stage is fieldwork, which main purpose is to observe the rock facies and sedimentological features of Lambir Formation in the study area. During field trip, apart from strike and dips measurement of beds, sedimentological logs will be drawn to record the key observations on each outcrop for facies interpretation purpose. The number of samples taken for petrophysical measurements is based on observable sandstone facies change at the outcrops. In the second stage of this study, the samples are prepared for porosity – permeability measurement by gas displacement method, using PoroPerm Coreval equipment for more accurate results. Blue dyed thin sections are prepared for observation of pores, pore connectivity, grain sizes and the geometry. Integration between microscale thin section analysis and macro scale field observations is the key of facies characterization.

CHAPTER 2

LITERATURE REVIEW

This chapter is a critical review of general geology of Lambir Formation in Baram Delta Province through numerous books and published research papers. Additionally, the fundamentals of important concepts such as facies analysis and petrophysical properties will also be discussed in details. All the information included in this chapter is essential in recognition and investigation of the formation in the field. Thus, the objectives of this project can be achieved with thorough understanding on these aspects.

2.1. GEOLOGICAL BACKGROUND OF LAMBIR FORMATION

Numbers of outcrop of Lambir Formation can also be found in Belait anticline, close to Kampong Labi, Brunei (Borren, et al., 1996). Lambir Formation in Brunei area is believed to be deposited in Berekas sub-basin with tidal influence whereas its counterpart in Miri was deposited in West Baram Delta, which is more wave- and tide-dominated (Simmons, et al., 1999). Curial, et al. (2000) mentioned that in Brunei, Lambir Formation together with Setap, Belait, Miri and Seria Formations are the essential elements of the petroleum bearing Champion Delta. In the article, Belait Formation had been discussed in details. The most part of Belait Formation was deposited in coastal and coastal plain environment, comprises dominantly fluvial sandstones with interbedded shales and coals. Lambir Formation, as laterally equivalent, is believed to be very much similar to Belait Formation but more marine. As Belait and Lambir Formations are not only geographically close but also high in similarity, to distinguish them in the field is rather a challenging task. However, Mohd Syamim Ramli and Padmanabhan (2011) introduced a list of distinguishing criteria that help differentiating the two formations based on several field characteristics. The main difference that makes Lambir Formation distinct from fluviatile Belait Formation is that it is more marine influenced. Thus, cross bedding features are more common in Lambir Formation and the ripple marks observed in

Lambir Formation are symmetrical instead of asymmetrical as such in Belait Formation. Mud or sand filled channels are very rare in Lambir Formation but more likely to present in Belait Formation. Moreover, it is also suggested in the paper that based on heterolithic sequences, Belait Formation contains higher clay content compared to Lambir Formation and on the other hand, massive sandstones appear to be more common in Lambir Formation. Although the differentiating characteristics are well discussed, they may not be available in all outcrops. Hence, it remains a challenge to distinguish the two formations at some locations.

In Miri area, the sandy Lambir Formation is underlain by thick Setap Shale and the sharp contact between these formations is cropped at the Southern area of Lambir hills (Jones, 1999; Hutchinson, 2005; Mazlan, 1999). Lambir Formation is interpreted to be deposited in shallow marine environment, consisting of predominantly sandstones, shale with some limestone and marl (Borren, et al., 1996; Hutchinson, 2005; Jones 1999; Simmons, et al., 1999). At Lambir Hills outcrops, the basal thickbedded sandstone of Lambir Formation has an erosive base, underlain by mudstone of Sibuti Formation or Setap Shale Formation (Simmons, et al., 1999; Tan, et al. 1999). Simmons, et al. (1999), in an extensive study on microfossil, suggested a possible unconformity at the contact between Setap Shale and Lambir Formation with the absence of earliest Mid Miocene rocks. Different sandstones facies in Lambir Formation suggested a transition of depositional conditions, from marine to coastal environment (Hutchinson, 2005).

In order to understand how depositional processes control reservoir properties, the sedimentological and petrophysical characteristics of sandstones must be determined. Teoh (2007) conducted a research on sedimentological and reservoir properties of Tertiary sandstones in Sabah and Sarawak. A comparison had been made among different sandstone samples from Miri Formation and a conclusion had been drawn that sandstone facies with better sorting and less clay content possess higher reservoir quality (porosity > 20%, permeability > 10mD). As Lambir Formation is older compared to Miri Formation, it may undergo greater compaction and alteration. Therefore, the reservoir quality of Lambir Formation is expected to be relatively lower than Miri Formation. Recently, Teoh and Hadi (2009) presented a comparative analysis on sedimentological and reservoir properties of sandstones belonging to Miri Formation (Miri) and Nyalau Formation (Bintulu). In the study, sandstones lithofacies had been categorized based on lithology, sedimentary structures, fossil traces and bed geometry. The relationship between permeability and porosity, density and porosity, velocity and porosity had been built for those lithofacies.

2.2. FACIES ANALYSIS

The main purpose of facies analysis is to understand the origin of sedimentary rocks through distinguishable descriptive features of these rock units. Different rock facies represents different physical, chemical as well as biological processes during deposition of the rock. At outcrop, rock facies can be classified based on colour, sedimentary structure, texture, geometry, bedding and fossils (Reading, 2001). Other than that, parameters such as grain size and bed thickness are also important and must be determined.

2.2.1. Bedding and lamination

These two terms refer to stratification of rocks/sediments and differentiated based on estimation of thickness. Generally, stratification with thickness greater than 1cm is called bedding whereas those thinner than 1cm are called lamination. Defining bedding and lamination is merely based on changes in sediment size, colour and/or composition. In field observation, thickness, geometry and contacts of both bedding and lamination are good indicators of depositional processes. In example, parallel bedding represents low energy and more or less stable deposition of sediments whereas wavy bedding can be interpreted as unstable deposition processes.

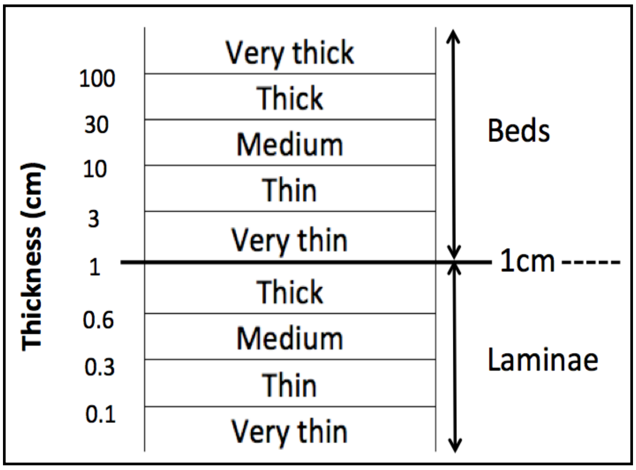

Figure 3 - Thickness and standard terminology for beds and laminae. (Stow, 2005).

2.2.2. Primary structures

Stratifications are formed mainly by deposition of sediments under the influence of numbers of processes. Below are some of the most common types of stratification that can be encountered on field:

- Parallel lamination/bedding: this is the most common form of stratification, which can be further classified into different types and origins based on difference in flow velocity, grain size, grain alignment, colour and composition.

- Wavy, lenticular and flaser lamination/bed: these types of lamination comprise both sand and mud but differ in sand/mud ratio. In flaser bed/lamination, the amount of sand exceeds mud deposits. Therefore, sand ripples are associated with mud drapes. Wavy bed/lamination, on the other hand, has sand/mud ratio of approximately 0.5. Stratifications are in forms of interconnected low-relief sand ripples bounded by muds. Lenticular stratification has least sand content, sand lenses are discontinuous and distributed within muddy layer.

- Cross stratification: generally, any horizontal unit what has internal structure comprises inclined bedforms such as lenses, ripples and dunes can be called cross stratification. Cross stratification can be further classified based on scale of set height and lamination/bed thickness.

- Graded bedding: grain size changes systematically within a bed can be either decreasing upward (normal grading) or increasing upward (reverse grading). Normal grading can be the result of either decreasing in depositional energy or rapid deposition of sediments (turbidite) that cause the heavy grains to settle down first, followed by lighter particles. Reverse grading is less common and normally formed due to debris flow.

- Structureless bedding: this type of bedding has no internal depositional structure, indicating event of rapid deposition that structure was not able to develop. Structureless beds are sometimes called massive beds but this, however does not mean that the bed has great thickness.

Previously, Abdul Hadi Abd. Rahman, in his PhD thesis, introduced a detailed facies analysis of Miri Formation, which characterized 9 different sandstone facies based on the lithology, bed geometry, sedimentary structures and bioturbation (Tan, et al., 1999). These descriptions can be used as reference for sandstone facies of Lambir Formation as the depositional history is similar between these two formations.

- **Facies 1**: Medium-scale trough cross-bedded facies: a sandstone bed with maximum thickness of 1m consists grains of fine to medium size. Cross-bedding can be observed along with large scale trough (wavelength of 0.1 to 3m). Some of this facies are associated with little amount of mud drapes and mud clasts whereas the rest are clean. With the presence of trough cross-bedded, this facies is interpreted as originated in shallow sub-tidal parts of a tide-dominated estuary.

- **Facies 2**: Small-scale trough cross-bedded facies: a trough cross-bedded facies of approximately 15 cm thick sandwiched in between mud drapes indicating possible ebb-flow run-off.

- **Facies 3**: Herringbone cross-bedded facies: change of dip direction of two adjacent cross-beds is always referred as indicator of tidal influence on deposition. The herringbone cross-beds observed in Miri Formation are distinctive with the separation of the two cross-bedded units by a thin mud layer.

- **Facies 4**: Flaser-bedded facies: in shallow sub-tidal and inter-tidal settings, alternative depositions of sand and mud with sand being more dominant results in cross-bedded sand layers with associated mud flasers.

- **Facies 5**: Wavy bedded facies: characterized by sand ripples overlain by a thin mud layer. This type of facies is possibly formed in mixed inter-tidal flats.

- **Facies 6**: Sand-clay alternation facies: sand layers of 1 to 20cm are interbedded with thin mud layers, which is the result of a low-current setting deposition.

- **Facies 7**: Lenticular-bedded facies: this facies is characterized by sand lenses embedded in mud with the sand thickness not more than a quarter of mud thickness. Low current or wave actions of sub-tidal to inter-tidal zones form isolated sand ripples on the clay beds. As the process is interrupted, these sand bodies are later on covered by clay deposition.

- **Facies 8**: Hummocky cross-stratified sandstone facies: a shallow marine deposit comprises fine-grained sand sheets in either sand/shale interbeds or thick massive sandstone (15cm to 90cm). Low angle cross-stratification is observable on the sandstones. Hummocky cross-stratification is considered as indicator of storm waves influence.

- **Facies 9**: Massive sandstone facies: massive sandstone is the term used for sandstone without sedimentary structures. In shallow marine environment, massive sandstones can possibly be deposited from density currents created by storm or hurricane.

Lambir Formation and Miri Formation were both deposited in shallow marine settings. Therefore, the sandstone facies in Lambir Formation are expected to display more or less similar features as those that had been described in Miri Formation. The interpretation of facies and depositional environments of Lambir Formation in a larger scale is important as an input in geostatistical models with better understanding on the distribution trend of Lambir Formation sandstone facies offshore.

2.3. PETROPHYSICAL PROPERTIES

In sandstone reservoirs, the petrophysical properties such as density, porosity and permeability are very important because they are the main factors that determine the reservoir quality. Porosity is a term for void spaces in a rock body that are not occupied by solid constituents (Teoh, 2007). Effective porosity is the type of porosity that should be considered for reservoir quality determination. Different from total porosity, it is defined by the pore spaces that are interconnected so that fluids are able to migrate from one to another place within the rock. Permeability, on the other hand, is defined as the feasibility of fluid flow in the rock (Teoh, 2007). Given interconnected porosity, as the pore throat size is smaller, the fluid flow is restricted and the rock is considered as low permeability.

Porosity and permeability of rocks are two different characteristics but both dependent on grain sizes, grain sorting, and grain geometry. These characteristics are directly linked to the processes and differ from one to another depositional environments. Grain size has no effect on porosity but for permeability, as grain size increases, the pore throat will also increase and thus, permeability is significantly higher. Sorting degree also has certain influence on permeability although not as much as grain size. In case of poor sorting, smaller particles tend to occupy the available spaces between large particles thus, produces lower rock permeability and porosity compared to well sorting. In structureless sandstone, permeability distribution is more or less homogeneous. However, in most cases, including layered sandstones, rock permeability is not isotropy, horizontal permeability is greater than vertical permeability most of the time (Meyer, 2002).

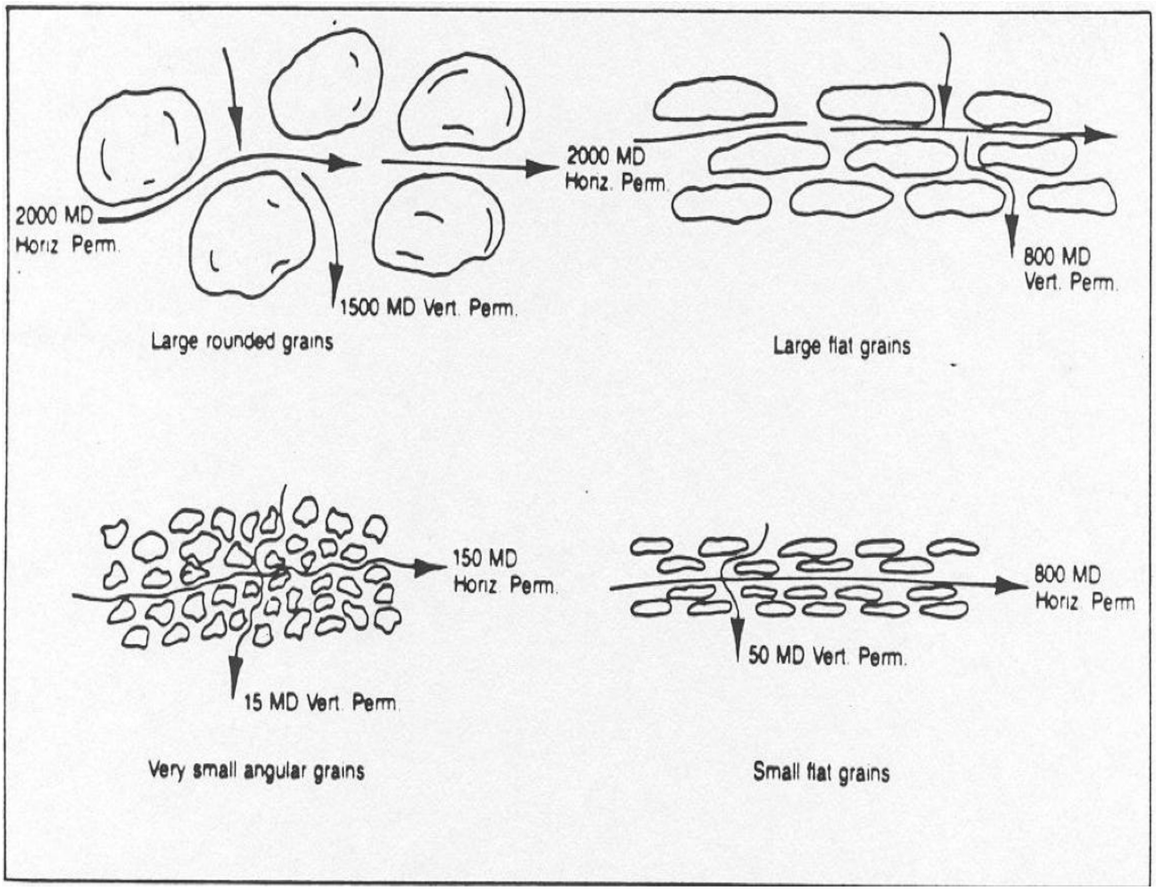

Figure 4 - Grain geometry and permeability (Link, 1982)
(cited in Permeability, 2010).

Another physical properties that significantly change among different rock types and facies is density. Density of rock at the outcrop can be measured in laboratory and thus, the distribution of underground rock density can also be predicted for further subsurface reservoir characterization and modeling. As much as petrophysical properties of a reservoir rock depend on the types of sedimentary facies, they are the end result of both depositional processes and diagenetic processes. Many studies had been carried out to determine the role of these processes on reservoir qualities (Seemann, 1982; Lima & Ros, 2002; Zhang, et al., 2008; Gier, et al., 2008; Mansurbeg, et al., 2008; Islam, 2009).

Generally, three main diagenesis processes that can alter primary porosity of reservoir rocks are: compaction, cementation and dissolution. Compaction and cementation reduces the porosity of rocks whereas dissolution helps enhance porosity and perpeability. Besides, sedimentological environment plays an important role in rock fragments content and sorting. Normally, sandstones formed in high energy environment are well sorted, coarse-grained and high quartz content. Low clay content contributes to high porosity and permeability characteristics of the rock. Rigid quartz grains are more resistant to compression, thus intergranular porosity is less destroyed during diagenesis. However, Hutchinson (2005) mentioned that the Lambir Formation had undergone little diagenesis, which means that the primary porosity of the sandstone beds could possibly be well preserved.

CHAPTER 3

METHODOLOGY AND PROJECT WORK

In order to achieve the objectives of this project, the methodology used in a study by Teoh & Hadi (2009) will be adapted for this project. However, grain size analysis by sieving method was excluded. Instead, information on grain size and shape is acquired by thin section digital image analysis. Sedimentological analysis was based mostly on field observation and literature review.

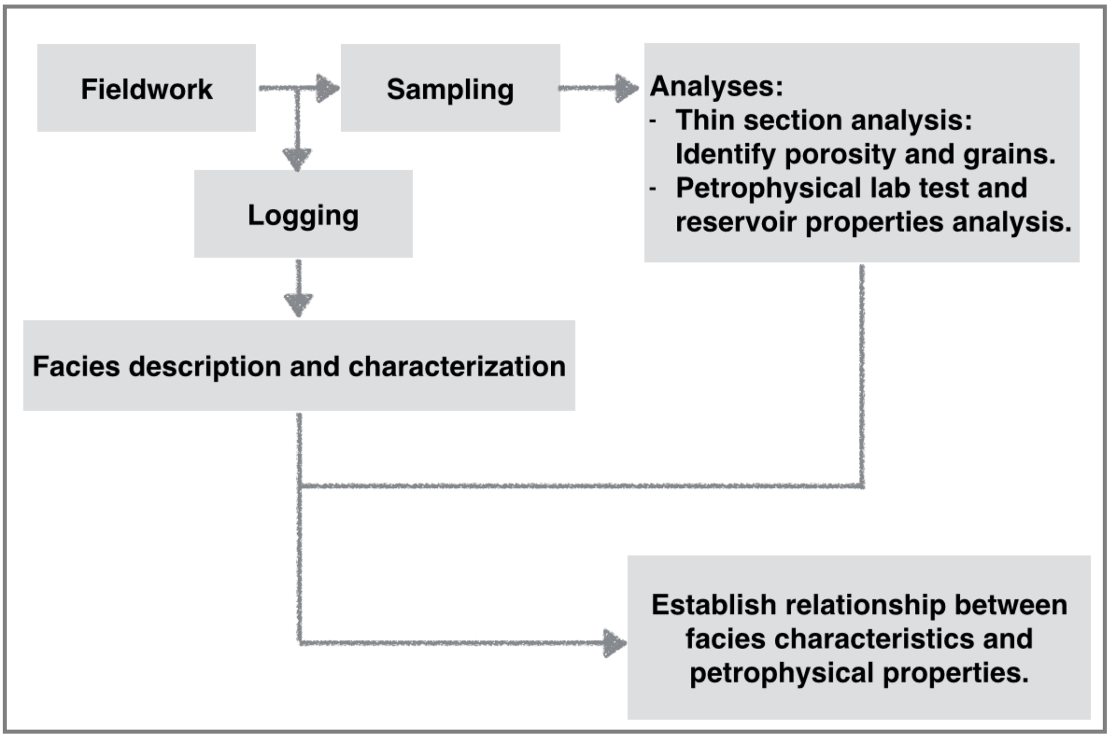

Figure 5 - Methodology flow chart.

3.1. FIELD WORK AND SEDIMENTOLOGICAL ANALYSIS

20 days of field trip had been carried out in Miri, Sarawak. Data collection had been done merely along the coastline (Southwest of Miri) as Lambir Formation is believed to be exposed in this area, according to map introduced by Kessler and Yong. Field measurements (strike, dip of beds, and strike of faults) had been taken to contribute to the construction of geological map and cross section. Structural readings were taken mostly along the traverse line starting from Peliau beach, whereas sedimentological log and sample collection were done at the two outcrops located at Tusan beach as clearly shown in the geological map (Figure **6**).

With a topographic map as base map, GPS coordinates as well as structural readings recorded at each waypoint and outcrop had been put on it to build the geological map. Furthermore, stratigraphic log were also drawn for each outcrop to determine different sandstone facies. Descriptions start from the base of the exposed part of Lambir Formation at the outcrops. Basically, bed thickness, mean grain sizes and physical characteristics are recorded on log paper. In addition, color, bedding, texture, and geometry were also noted. All the characteristics above are gathered in order to determine the following: lithology, bedding geometry, sedimentary structures, and direction of beds. Samples were collected upon changes in sandstone facies with sufficient volume for making of core plugs and thin sections. Six sandstone samples had been collected upon changes in sandstone facies with sufficient volume for thin section analysis and petrophysical measurements. Three of the samples belong to trough cross beds, two are from hummocky cross beds, and one is from herringbone cross bed.

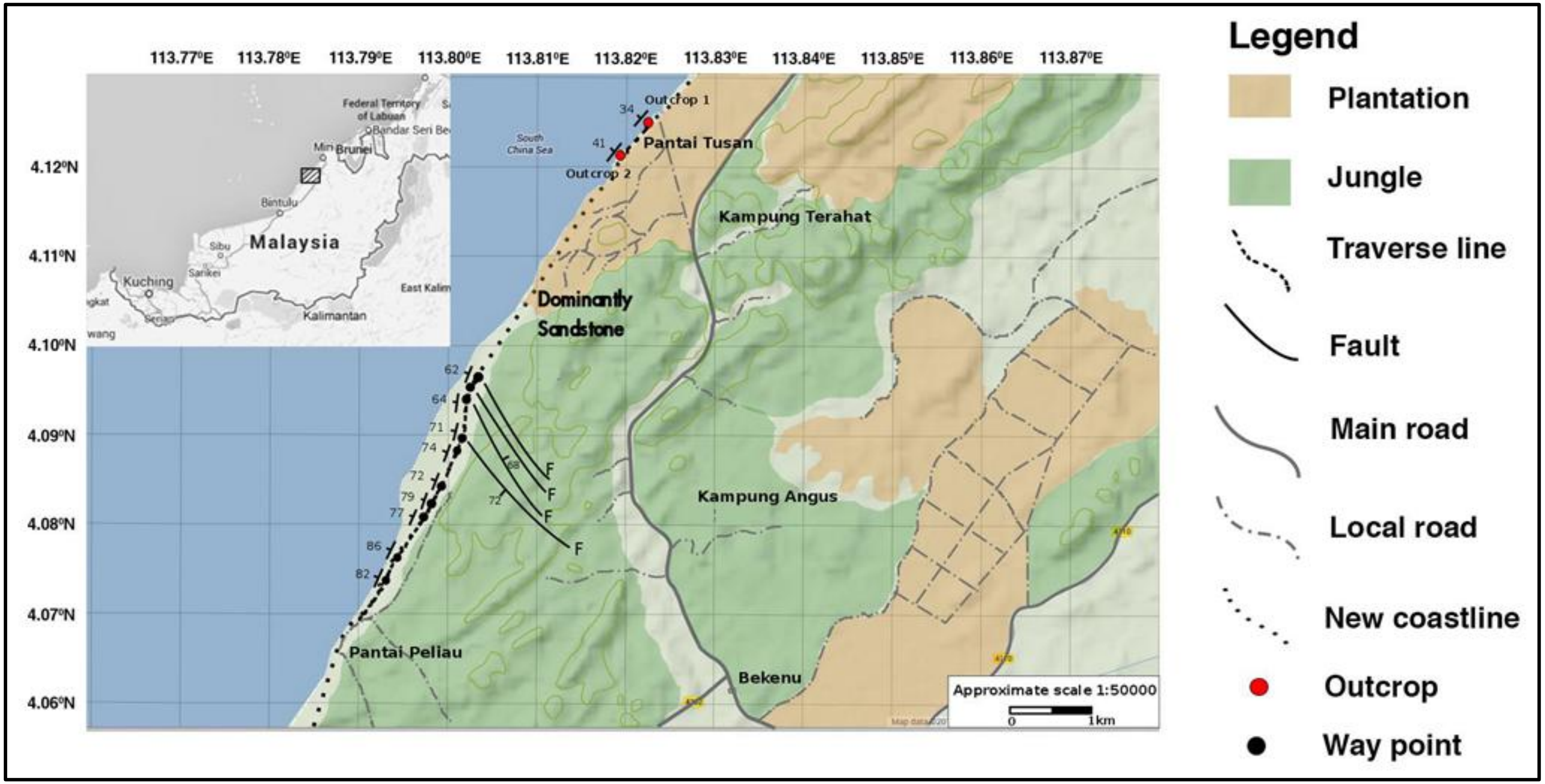

Figure 6 - Map showing traverse line and study area.

3.2. BLUE-DYED THIN SECTION IMAGE ANALYSIS

Petrographic Image Analysis (PIA) technique had been discussed by many authors (Francus, 1998; Buscombe, 2008; Layman II, 2002; Dastgerdi, et al., 1390; Medina, 2013; Viet, 2010). Porosity characterization as well as grain size measurement can be done with PIA technique. Layman II (2002) concluded in his master thesis that image analysis is applicable and can be a substitute for determining porosity, instead of using core analysis or standard petrographic methods. Basically, the technique consists of 4 main steps:

- Sample preparation: blue-dyed thin sections.
- Image acquisition: image of thin sections were observed and recorded.
- Image processing: images were converted into gray-scale with measurement scale set. Threshold was adjusted so that all black pixels, which represent porosity, are filled with red colour.
- Images measurement: red-filled area was measured and the porosity is obtained as fraction between the area of black pixels and the whole image.

Void spaces, which appears in blue colour, can be distinguished from grains, matrix and cement under 2D Microscopic view, allowing for better recognition of pore connectivity. Thin sections were described to serve the purpose of identifying grains, pores, sorting and interpreting depositional facies. Information on pore types, pore geometry and porosity can be integrated with petrophysical measurements to assess the reservoir quality. The thin section images were analyzed by “ImageJ” software to acquire estimations of porosity and grain size. Classification of grains was based on Udden-Wentworth grain size classification scheme.

Millimeters (mm)		Micrometers (µm)	Phi (φ)	Wentworth size class		Rock type
	4096		-12.0	Boulder	Gravel	Conglomerate/ Breccia
	256		-8.0	Cobble		
	64		-6.0	Pebble		
	4		-2.0	Granule		
	2.00		-1.0	Very coarse sand	Sand	Sandstone
	1.00		0.0	Coarse sand		
1/2	0.50	500	1.0	Medium sand		
1/4	0.25	250	2.0	Fine sand		
1/8	0.125	125	3.0	Very fine sand		
1/16	0.0625	63	4.0	Coarse silt	Silt	Siltstone
1/32	0.031	31	5.0	Medium silt		
1/64	0.0156	15.6	6.0	Fine silt		
1/128	0.0078	7.8	7.0	Very fine silt		
1/256	0.0039	3.9	8.0	Clay	Mud	Claystone
	0.00006	0.06	14.0			

Figure 7 - Udden-Wentworth grain size classification scheme. (Blair & McPherson, 2004)

Sandstone samples had been dyed with blue epoxy in order to enhance the estimation of porosity. Photos of thin sections under microscope were taken using LEICA DM750P Microscope, which is attached with a computer.

Figure 8 - LEICA DM750P Microscope.

Digital images were processed using compatible software. After setting image scale, measurement of grain sizes had been done to verify and compare with sedimentological logs. Furthermore, images of thin sections were loaded into ImageJ software for porosity estimation:

1) First of all, the images were converted to 32-bit greyscale image so that the software can differentiate between porosity and quart grains based on differences in brightness.
2) After that, brightness threshold was set to define the window of brightness. The porosity is displayed in red colour, brightness threshold can be adjusted to acquire desired porosity area.
3) The last step is selecting "Measure" function, and the results are shown as percentage of area. Porosity values obtained from thin section images can be correlated with measurement done by POROPERM instrument.

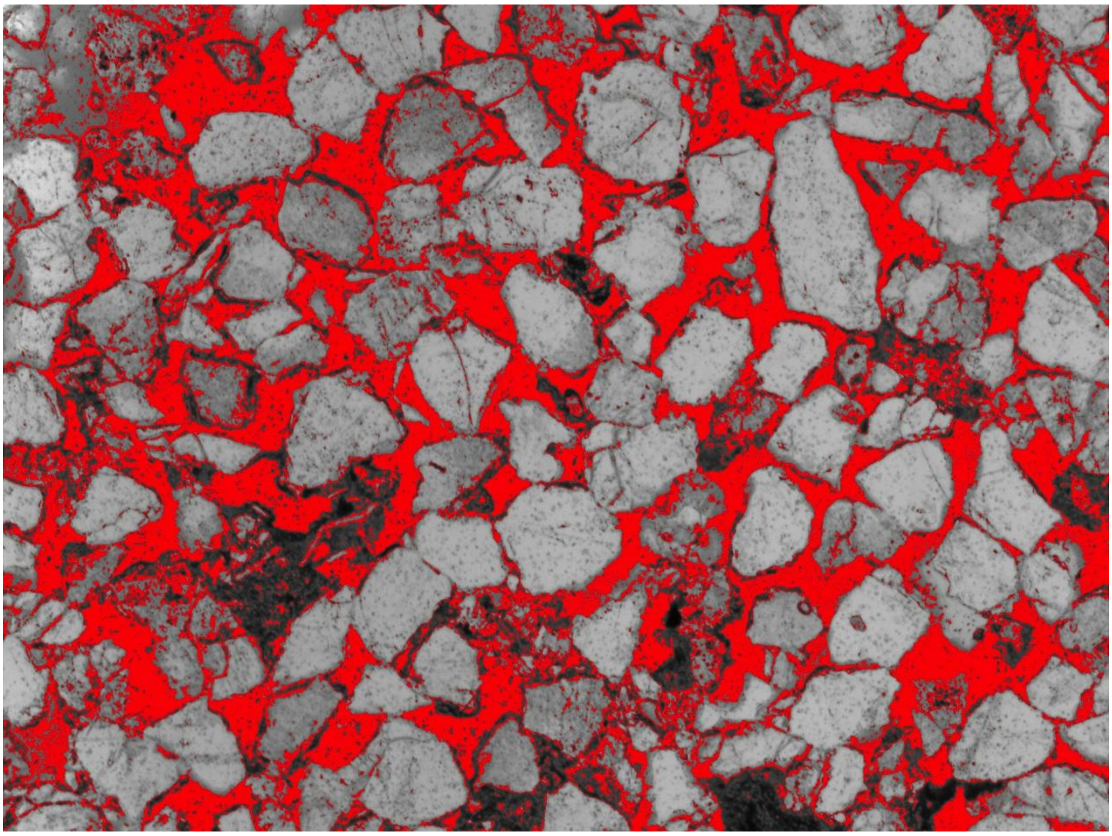

Figure 9 - Porosity presented in red color in ImageJ software. Estimated porosity is 26.7% (Sandstone 2).

3.3. PETROPHYSICAL PARAMETERS MEASUREMENTS

Measurements for determining the reservoir petrophysical properties are porosity, permeability, and density. All these parameters can be measured by POROPERM instrument following ISO standard:

1) Core holder size was selected as 1.5inch size.
2) The sample was put into the core holder.
3) Core holder was tightly locked.
4) Core holder was pressurized.
5) Core information including Sample ID, Diameter, Length, Weight, and Atmospheric Pressure was input into the software.
6) Measurement started by clicking on the button “Start Measure”.
7) Steps 1 to 6 were repeated for every sample.
8) The results were recorded in an excel file.

The direct measurements are: gas permeability, pore volume and core length/diameter. Gas permeability is measured based on unsteady state method (confining pressure decreases by time), whereas pore volume is determined by Boyle’s Law ($P_1V_1 = P_2V_2$) (Permeability, 2010). Additionally, the instrument also provides calculation of other parameters such as Klinkenberg slip factor “b”, Klinkenberg corrected permeability, inertial coefficients, sample bulk volume, sample effective porosity, grain volume and grain density. In measurement of permeability, the calculated permeability by POROPERM instrument maybe greater than the true permeability of rock sample due to Klinkenberg’s effect. This happens when gas is used to measure rock permeability at low pressure condition. Gas molecules flow faster due to diffusion instead of pressure difference. However, increasing pressure can significantly reduce the effect (Permeability, 2010). The permeability of each rock facies will be measured in horizontal direction to examine the lateral migration of fluid. Porosity and permeability test results can be correlated and integrated with observations from thin section.

In this project, POROPERM COREVAL 30 instrument (Figure **10**) had been used to serve the purpose of measuring porosity, permeability and density of six sandstone cores. Prior to petrophysical measurements, rock samples had been prepared as cores with 1.5 inches diameter and 1 to 3 inches length (Figure **11**). During coring process, due to the friability of sandstone samples, there are some irregularities in core shape and size. This may significantly affects the measurements. Core samples are then put in the oven for 24 hours to dry up. The measuring results are recorded in the computer that is connected with the instrument. These results are shown in Chapter 4.

Figure 10 - POROPERM COREVAL 30 instrument.

Due to difficulties in coring friable samples, the resulting cores are of different lengths. For accurate results, core size was measured using digital caliper whereas digital weighing scale was used to record core mass.

Figure 11 - Core samples used for POROPERM test.

Table 1 - Core size and weight.

	Diameter (mm)	Length (mm)	Weight (g)
Sandstone 1	37.21	59.22	111.5
Sandstone 2	37.57	46.8	87.62
Sandstone 3	37.67	42.27	78.32
Sandstone 4	37.65	50.25	92.43
Sandstone 5	37.63	48.61	92.9
Sandstone 6	37.63	74.64	141.02

CHAPTER 4

RESULTS AND DISCUSSION

Generally, rock strata of Lambir Formation in this area have Northwest dip direction and decreasing dip angle towards North. Fractures are abundant on rocks exposed along the traverse line and are available as conjugate or orthogonal (up to 3 sets). On the opposite, only four significant faults can be observed with similar strike direction. Sandstone was the most dominant rock type in the map section and minor shale amount was encountered.

In terms of recognizing geological features, most of the distinguishing characteristics of Lambir Formation introduced by Mohd Syamim Ramli and Padmanabhan (2011) can be encountered in the survey area. Based on field observations, five main sandstone facies had been interpreted in total. Cross beddings are abundant in the formation. Trough cross beds are the most common lithofacies encountered. These are characterized by small scale cross bed sets, bounded by low angle curved surface. Other cross stratification features can also be seen at the outcrops, such as tabular cross beds, hummocky cross beds and herringbone cross beds. Massive (structureless) sandstone was present but with minor amount compare to other facies and is heavily weathered. Both outcrops have relatively high degree of bioturbation, 2 to 4 in average. Mud drapes in between bed sets are common, making the sedimentary features more revealing. Coal clasts and lenses with varied size can easily be found in both sandstone and mudstone layers. Two graphic logs had been drawn to illustrate and describe the outcrops (Figure **12** & Figure **13**).

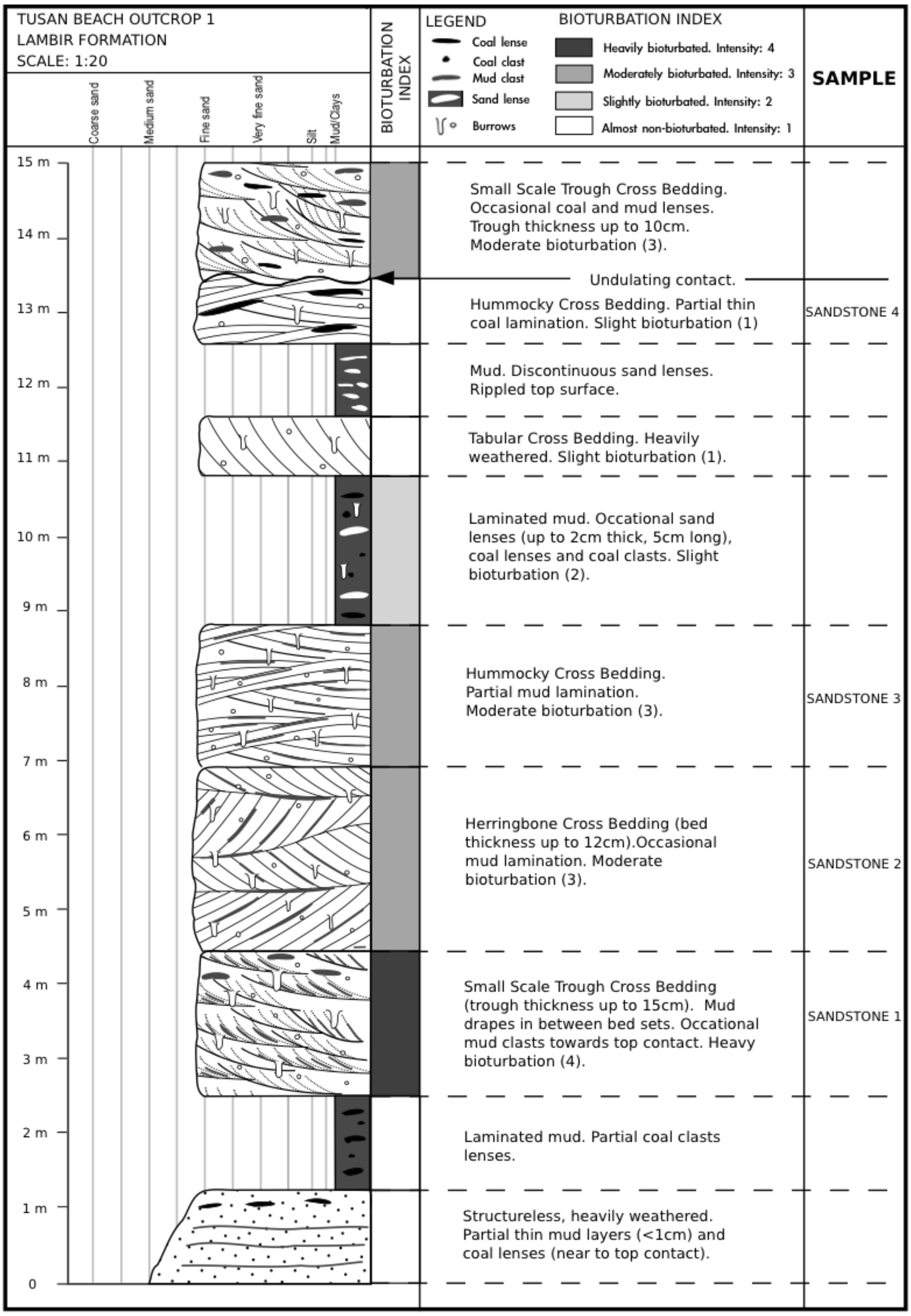

Figure 12 - Sedimentological log for outcrop 1.

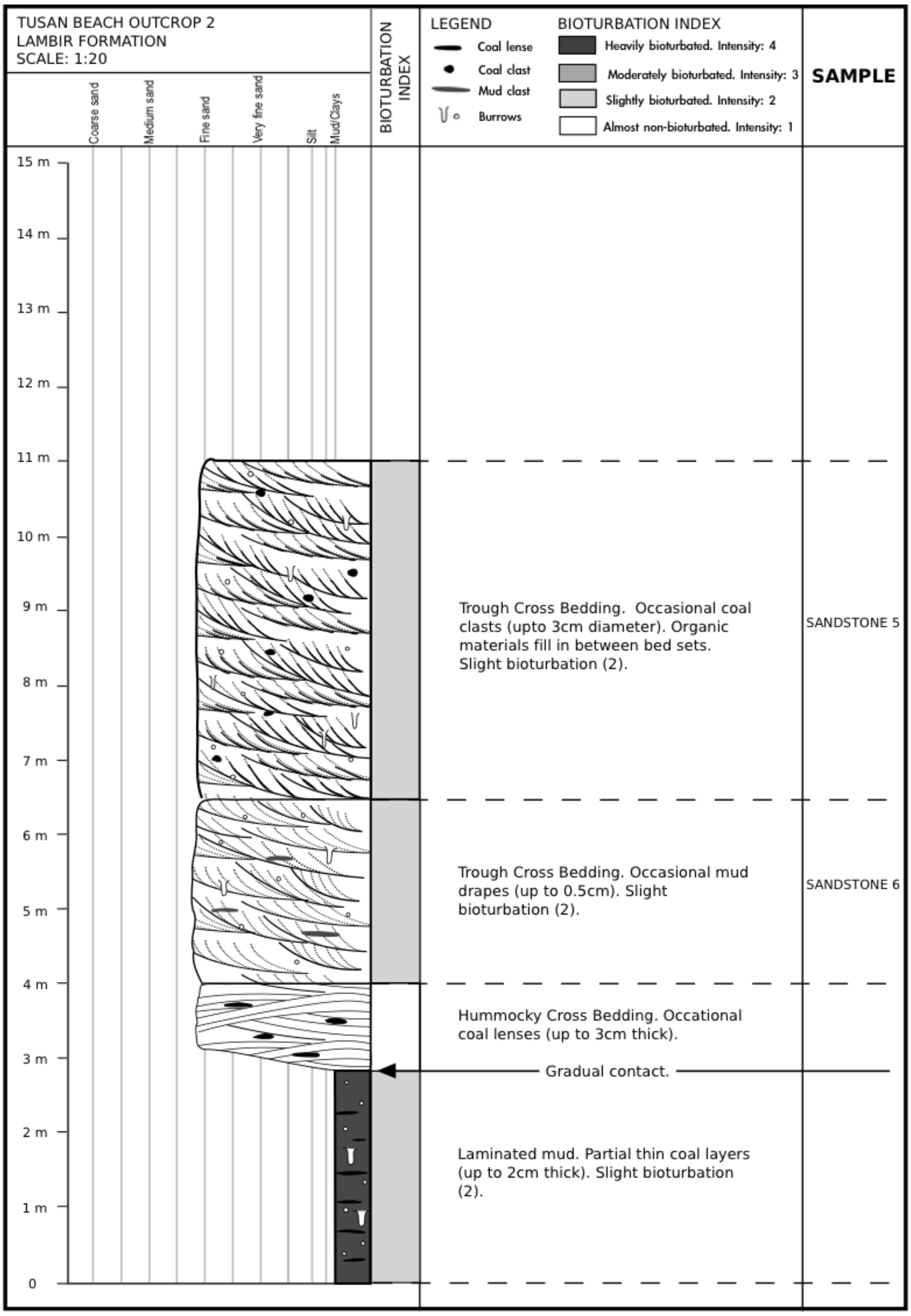

Figure 13 - Sedimentological log for outcrop 2.

4.1. SANDSTONE FACIES ANALYSIS

Most part of the formation in Tusan Beach is well sorted, although bioturbations are common, causing disturbance in the beddings.

Facies A: Massive/Structureless Sandstone.

Description: Facies A is characterized by structureless fine to medium grained sandstone. Thin mud layers, which are less than 1cm thick, are present as well as coal lenses towards top contact. The layer is heavily weathered without observable bioturbation. The whole section is approximately 1.2 meters.

Interpretation: massive sandstone in shallow marine setting can be interpreted as deposited above storm wave base after storm event (Hilderbrandt & Egenhoff, 2007). Thus, the bed shows no internal bedding structures or truncation surfaces.

Facies B: Trough Cross Bedded Sandstone

Description: Facies B consists of thinly laminated, fine grained sandstone with associated mud lenses. Individual cross beds are approximately 15cm thick with low angle curved base. Mud fills between laminations are common, making the sedimentary structure easier to be observed. The facies is heavily bioturbated, up to 4 degree. Core porosity value for this facies range from 32.9% to 39% and estimated porosity from thin section range from 26% to 28.7%. Horizontal permeability value range from 2455.4 mD to 3018.8 mD, vertical permeability is recorded as 1341.4 mD.

Interpretation: This facies is believed to be associated with estuaries and shallow sub-tidal settings (Abdul Hadi Abd. Rahman, 1995). Mud drapes in between bed sets are the indicator of periods without bed-load movement. In general, this facies can be interpreted as deposits in sub-tidal areas of tide-dominated estuary.

Facies C: Herringbone Cross Bedded Sandstone

Description: This facies is composed of thinly laminated, fine-grained, low angle cross-laminated sandstone. Two directions of lamination dipping can be observed. Thin mud layers are present in between bed sets. This facies has bioturbation up to 3 degree. Core porosity value for this facies is recorded as 35.5% and estimated porosity from thin section is recorded as 26.7%. Permeability value is 1105.3 mD.

Interpretation: Alternating strata of opposite-dipping cross beds indicate alternating currents. This suggests a tidal-influenced or intertidal deposition (Abdul Hadi Abd. Rahman, 1995).

Facies D: Tabular Cross Bedded Sandstone.

Description: Facies D comprises of fine-grained, parallel to undulating low angle (Nichols, 2009) cross-laminated sandstone. The facies is less than 1m thick and is almost non-bioturbated (1 degree).

Interpretation: Sharp erosional contact with mudrock below indicates that the bed can be related to storm event. This bed is separated with the above hummocky cross-bedded sandstone by a layer of mud, which had been reworked from the sea floor (Nichols, 2009).

Facies E: Hummocky Cross Bedded Sandstone.

Description: This facies is characterized by both concave up and convex up undulating cross-laminated, fine-grained sandstone. This facies contains thin coal lamination in between bed sets and is moderately bioturbated (3 degree). Core porosity value for this facies range from 32.8% to 34.3% and estimated porosity from thin section range from 25.3% to 26.5%. Horizontal permeability value is recorded as 2577.5 mD, vertical permeability is recorded as 1105.9 mD.

Interpretation: This facies can be interpreted as formed by storm influence. The low-angle hummocky cross stratifications were produced below fair weather base (Abdul Hadi Abd. Rahman, 1995). The stratigraphic position of these beds overlying intertidal herringbone cross-bedded sandstone indicate sudden rising of water level. In another scenario, hummocky cross-bedded sandstones can also be deposited on land when large storm brought up large amount of water onto the tidal flat (Woofe, 1993).

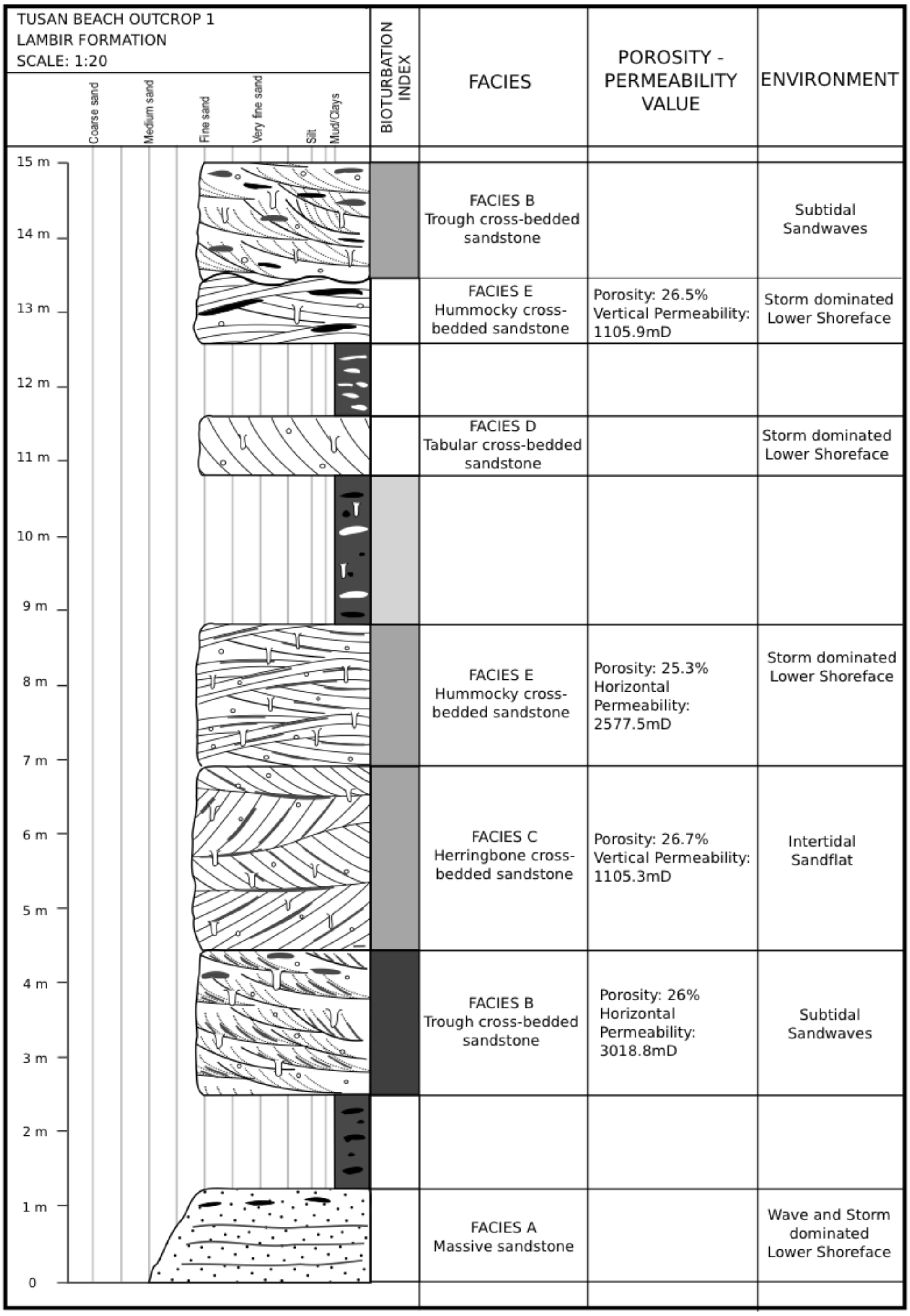

Figure 14 - Facies Analysis Stratigraphy of Outcrop 1.

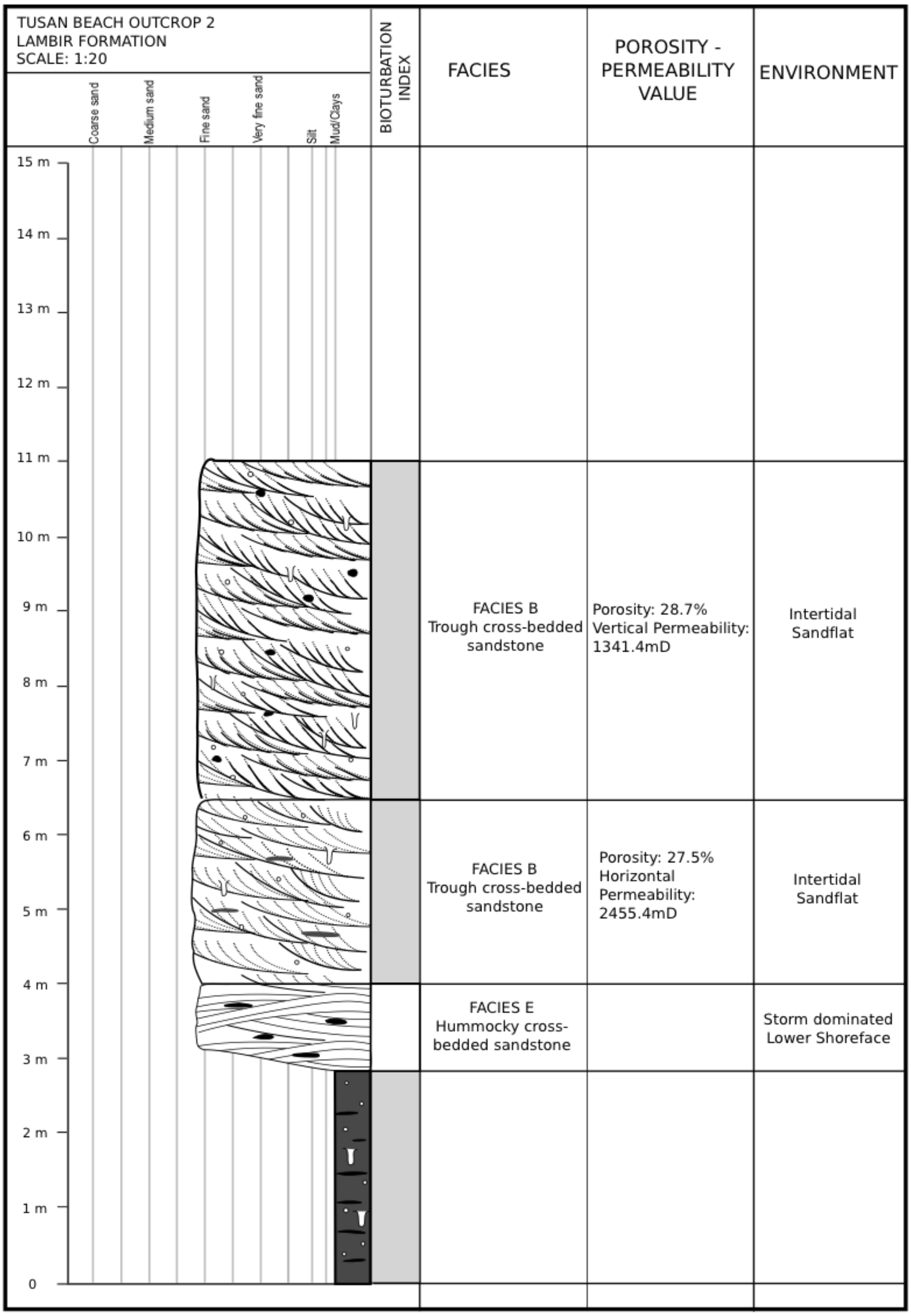

Figure 15 - Facies Analysis Stratigraphy of Outcrop 2.

4.2. THIN SECTION IMAGE ANALYSIS

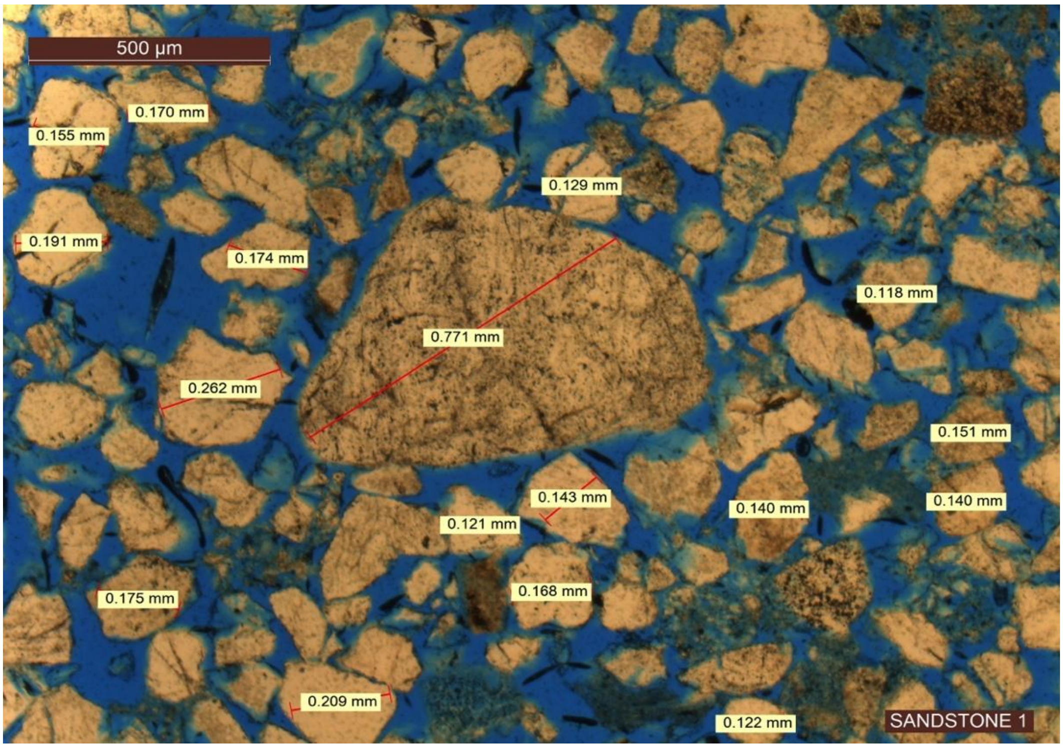

Figure 16 - Sandstone 1 thin section image.

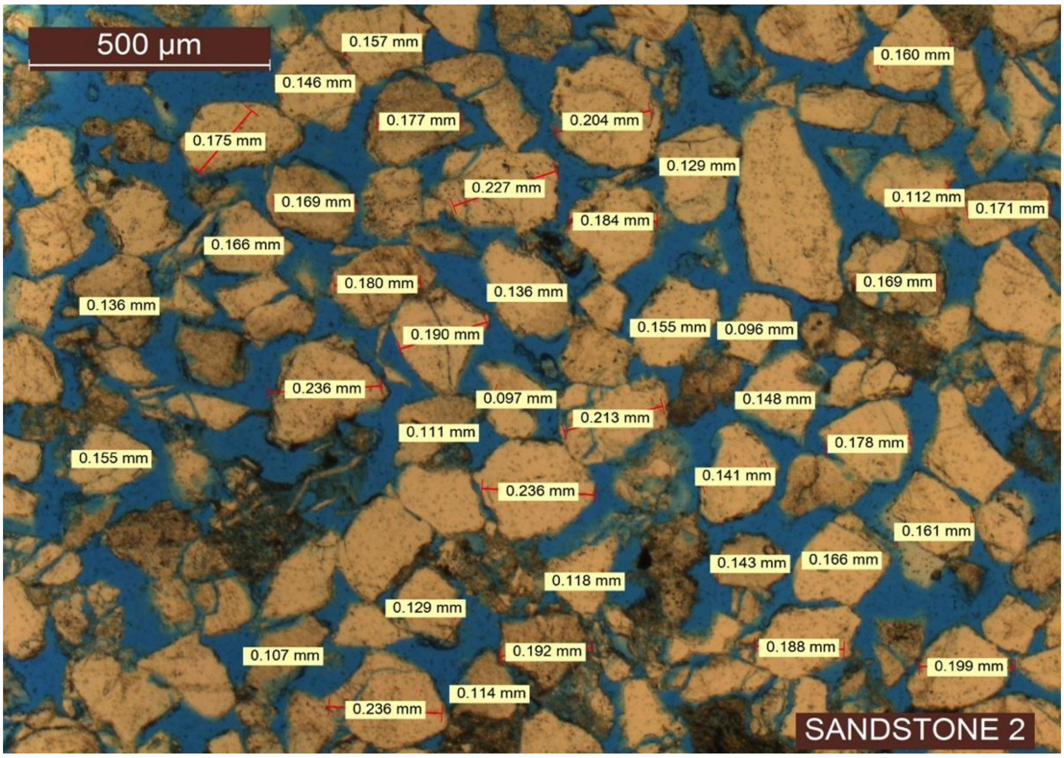

Figure 17 - Sandstone 2 thin section image.

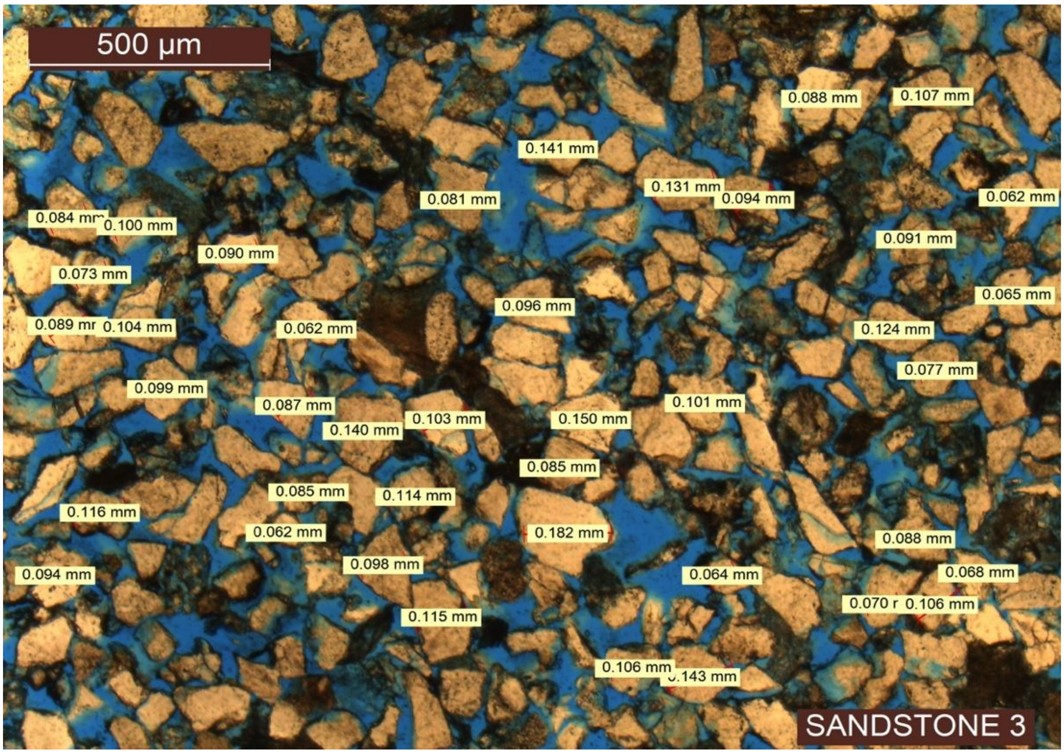

Figure 18 - Sandstone 3 thin section image.

Figure 19 - Sandstone 4 thin section image.

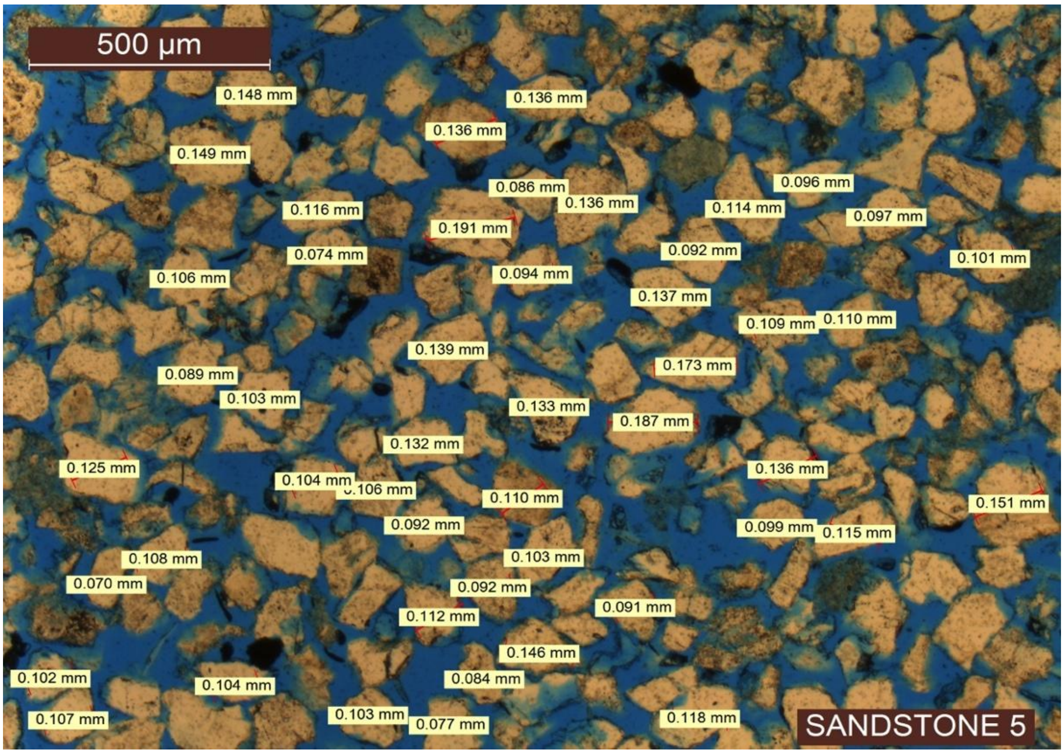

Figure 20 - Sandstone 5 thin section image.

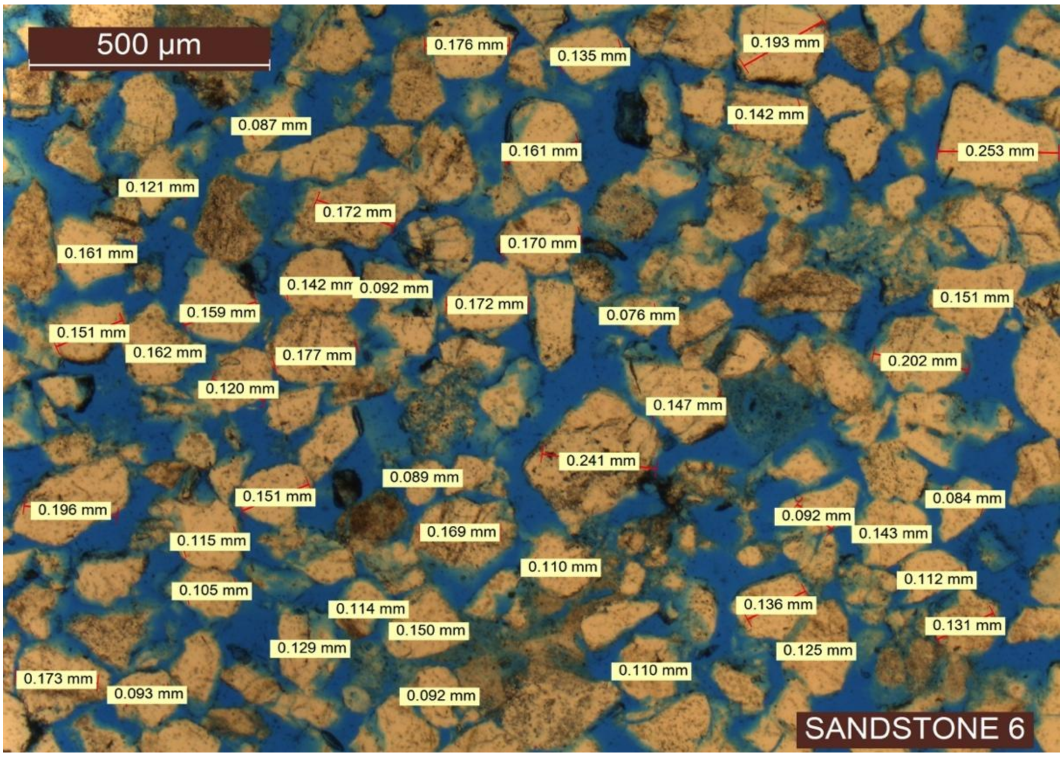

Figure 21 - Sandstone 6 thin section image.

It is clearly shown in the thin section images that the quartz grains are angular to sub-angular in all the samples. Amount of mud is very little in most of the thin sections except for Sandstone 3. Coal clasts can be seen in all samples, which were predicted based on field observation. With grain sizes measured from thin section images, a graph of grain size distribution is plotted.

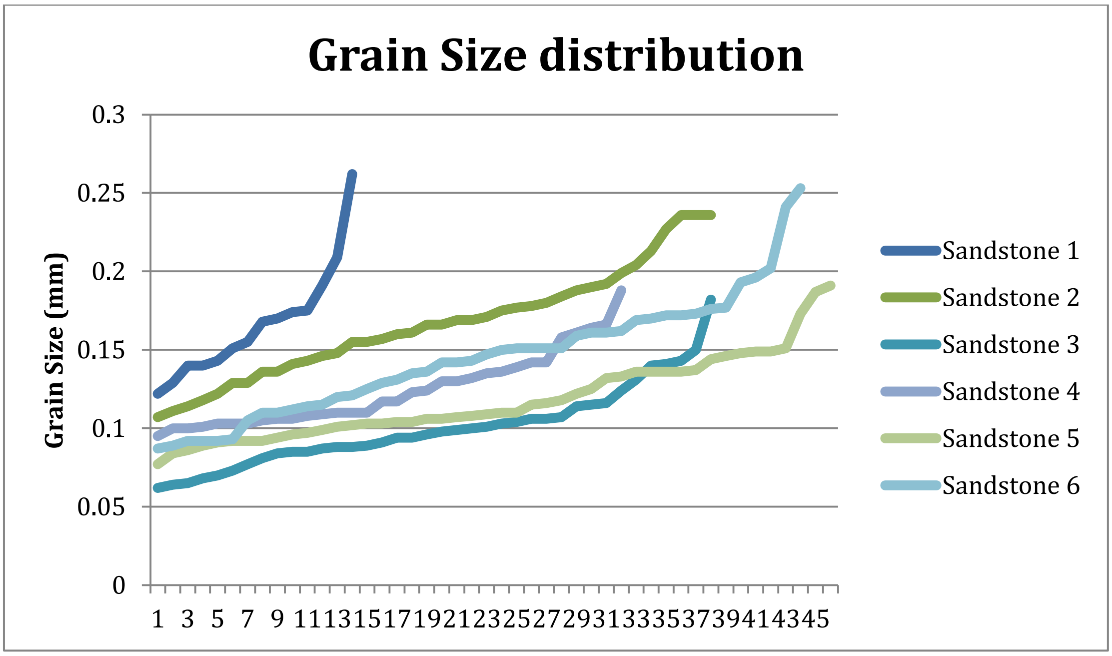

Figure 22 - Graph showing grain size distribution.

The graph shows that most of the grains are in range of 0.06mm to 0.25mm, which means that all six sandstone samples are very fine-grained to fine-grained (based on Udden-Wentworth scale). This is in accordance with field observations and sedimentological log descriptions of the beds.

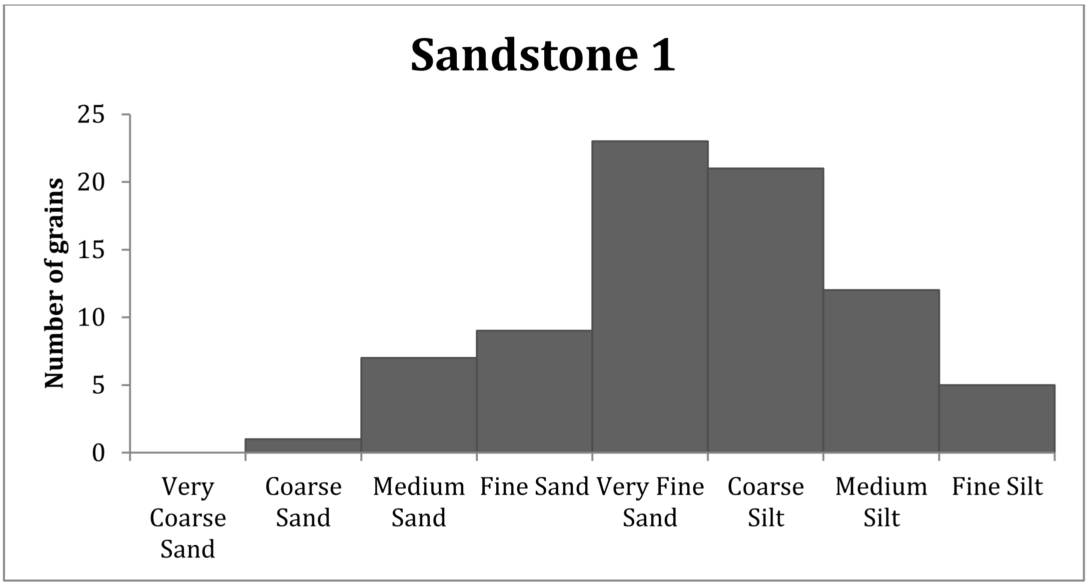

Figure 23 - Histogram for Sandstone 1, Lambir Formation.

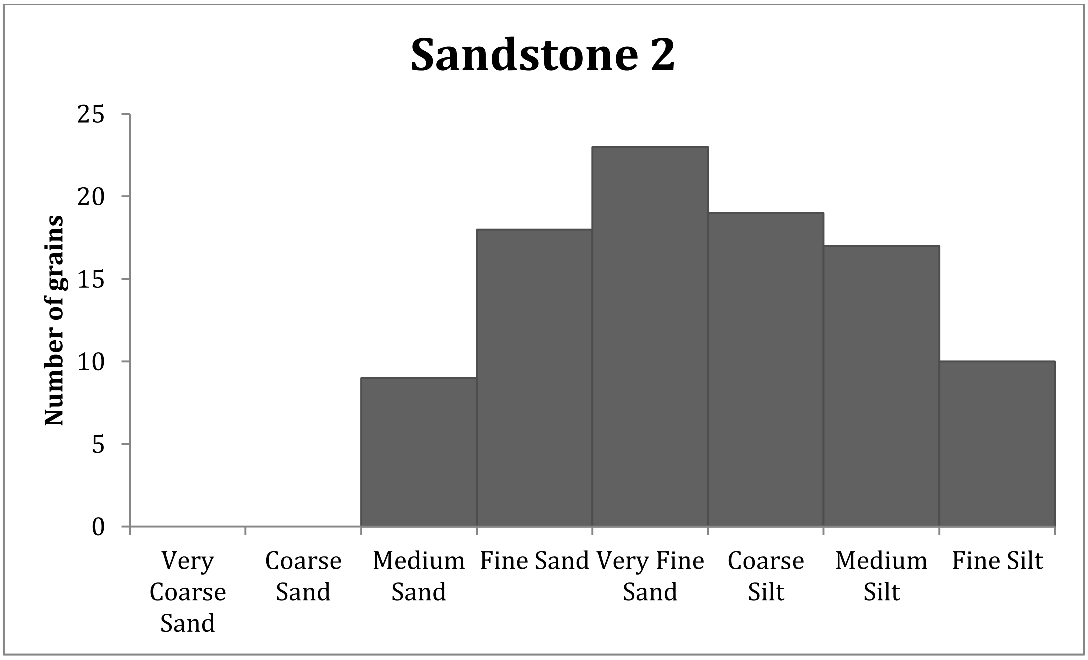

Figure 24 - Histogram for Sandstone 2, Lambir Formation.

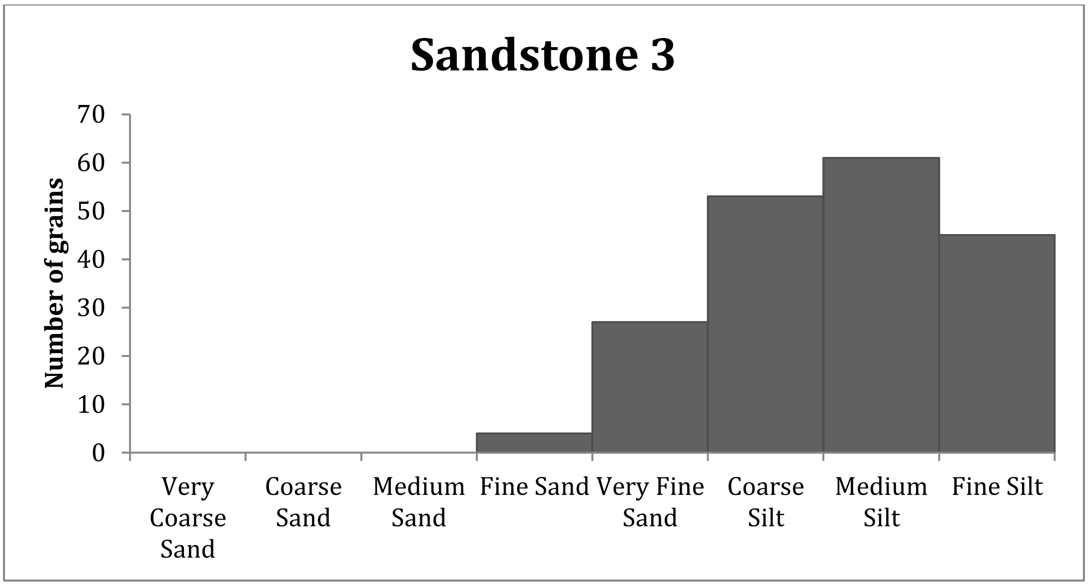

Figure 25 - Histogram for Sandstone 3, Lambir Formation.

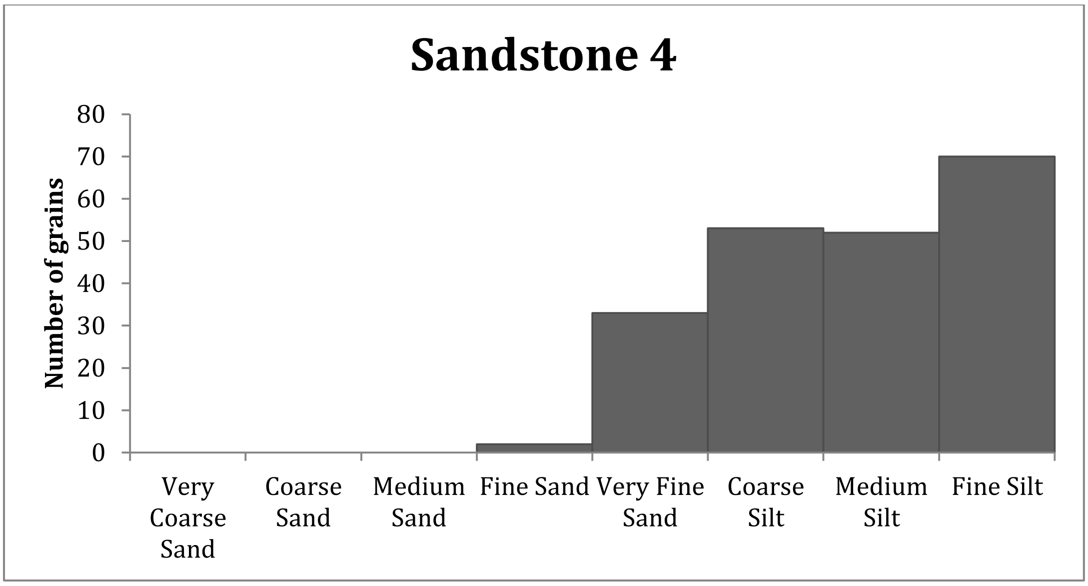

Figure 26 - Histogram for Sandstone 4, Lambir Formation.

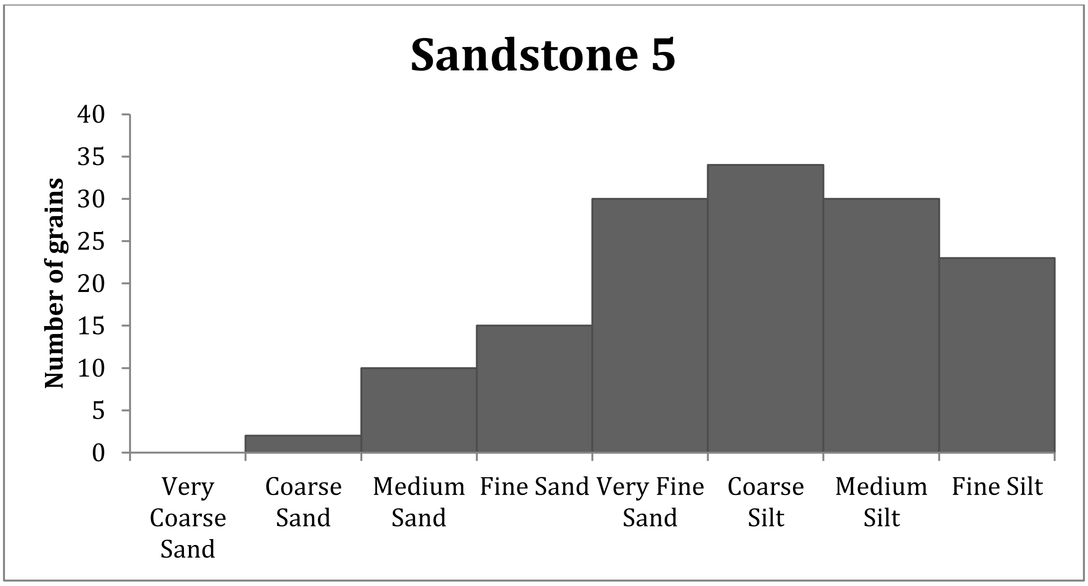

Figure 27 - Histogram for Sandstone 5, Lambir Formation.

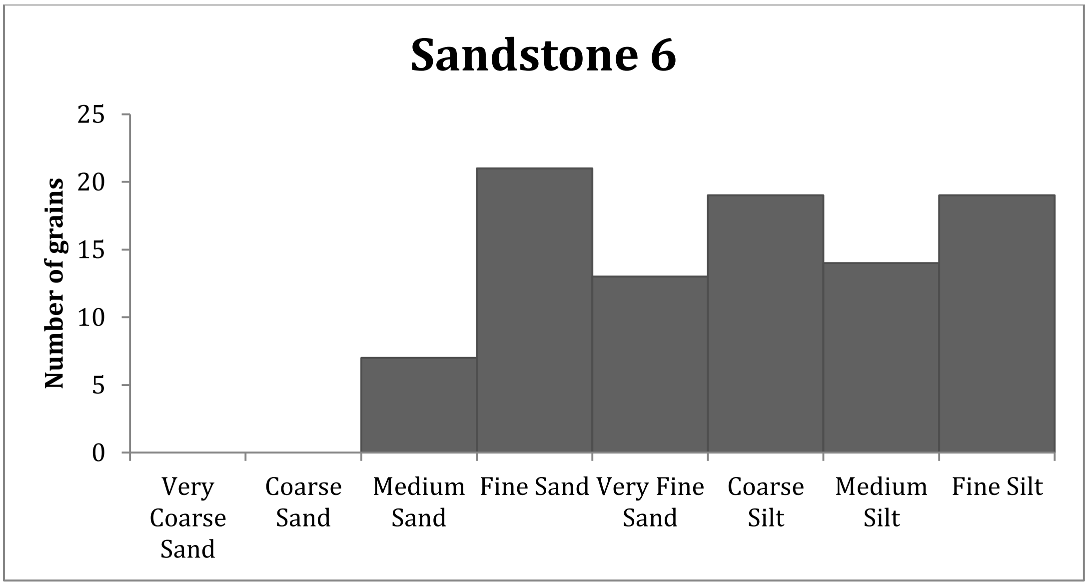

Figure 28 - Histogram for Sandstone 6, Lambir Formation.

4.3. PETROPHYSICAL PROPERTIES MEASUREMENT

Below are the tabulated results from petrophysical properties test and thin section analysis:

Table 2 - Results from POROPERM measurement and thin section analysis.

	Facies	Type of Permeability measured	Gas Permeability (mD)	Porosity by Poroperm (%)	Porosity by Image Analysis (%)	Bulk Density (g/cc)
Sandstone 1	Trough cross-bed	Horizontal	3018.8	32.9	26	1.73
Sandstone 2	Herringbone cross-bed	Vertical	1105.3	35.5	26.7	1.69
Sandstone 3	Hummocky cross-bed	Horizontal	2577.5	32.8	25.3	1.66
Sandstone 4	Hummocky cross-bed	Vertical	1105.9	34.3	26.5	1.65
Sandstone 5	Trough cross-bed	Vertical	1341.4	39	28.7	1.72
Sandstone 6	Trough cross-bed	Horizontal	2455.4	38.1	27.5	1.70

Thin sections of all six sandstone samples show similar feature, in which, pores are mostly interconnected. Thus, permeability and effective porosity are expected to be at high values. The prediction is confirmed by both results from POROPERM measurement and thin section analysis. Porosity obtained from thin section images has value range of 26% to 28.7% and POROPERM instrument delivered porosity values over 32%. Comparing these two methods, we can see that there are significant differences between the results obtained, which range from 6% to 11%. Thin section porosity estimation merely depends on the judgment of user when adjusting porosity threshold in the software, whereas measurement using POROPERM instrument requires the core samples to be in good shape. The irregularities in core shape (Figure **11**), which were formed during coring process, are interpreted to be main influencing factor that caused the abnormally high POROPERM porosity values. However, the true porosities of the samples are expected to be less than 30% and close to those estimated using thin section images. Therefore, porosity values obtained from image analysis will be used for plotting scattered diagrams and interpretation.

While porosity and density value of the samples do not have much difference, the permeability shows relatively high variation from one to another, with value ranges from 1105mD to 3018mD.

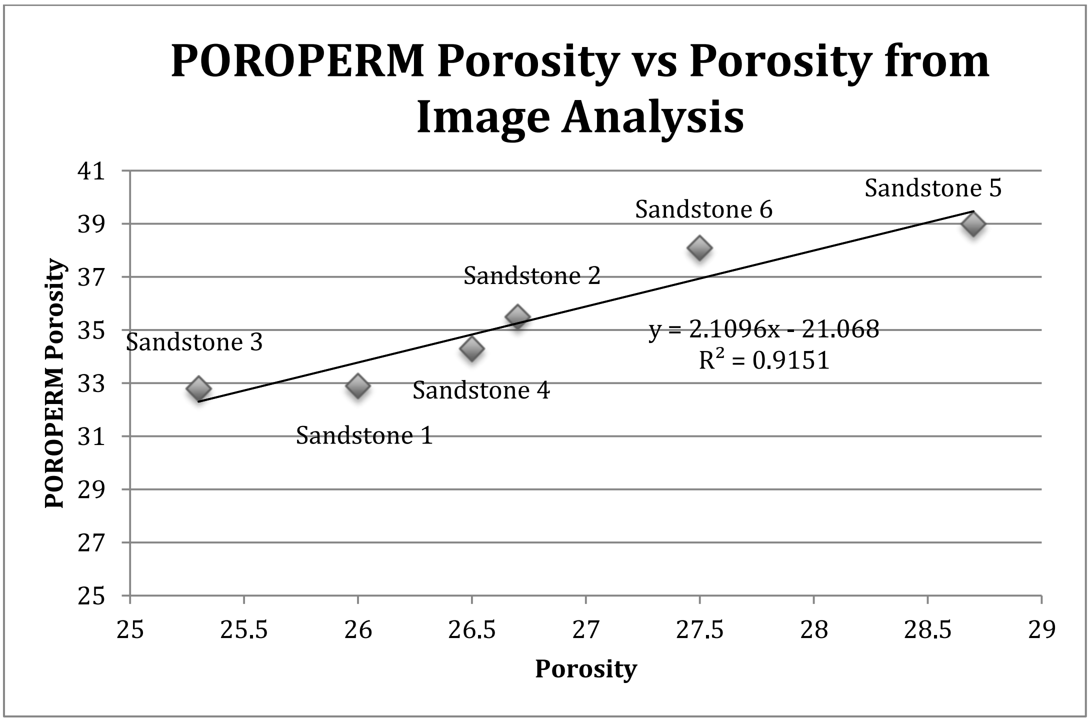

Figure 29 - Scattered diagram with regression line correlation POROPERM porosity and porosity from image analysis.

Regardless of the differences between POROPERM and thin section estimated porosity, the cross-plot of these two data sets show good coefficient of correlation (R^2 = 0.91506). This means porosity values obtained from the two methods are reliable and the trend of increasing porosity among the samples is consistent.

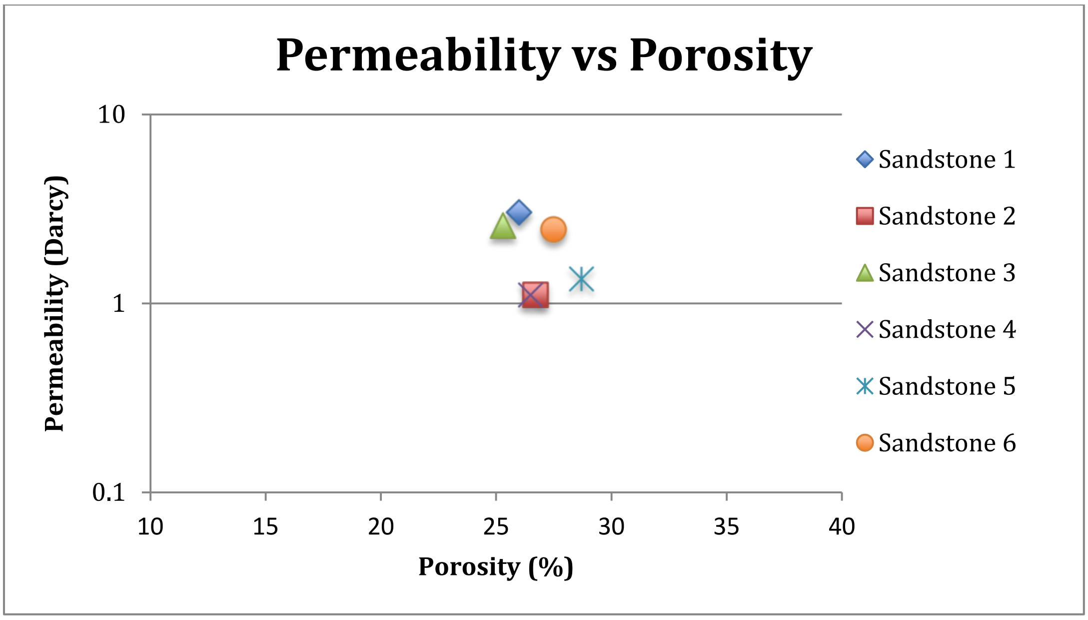

Figure 30 – Cross-plot between permeability and porosity acquired from Image analysis.

Figure **30** shows permeability and image porosity cross-plot for the six samples. The sandstones show a dispersed permeability – porosity relationship. The sandstones can be divided into two groups. Very high permeability – Very high porosity (sandstone 1, sandstone 3, sandstone 6) and High permeability – Very high porosity (sandstone 2, sandstone 4, sandstone 5).

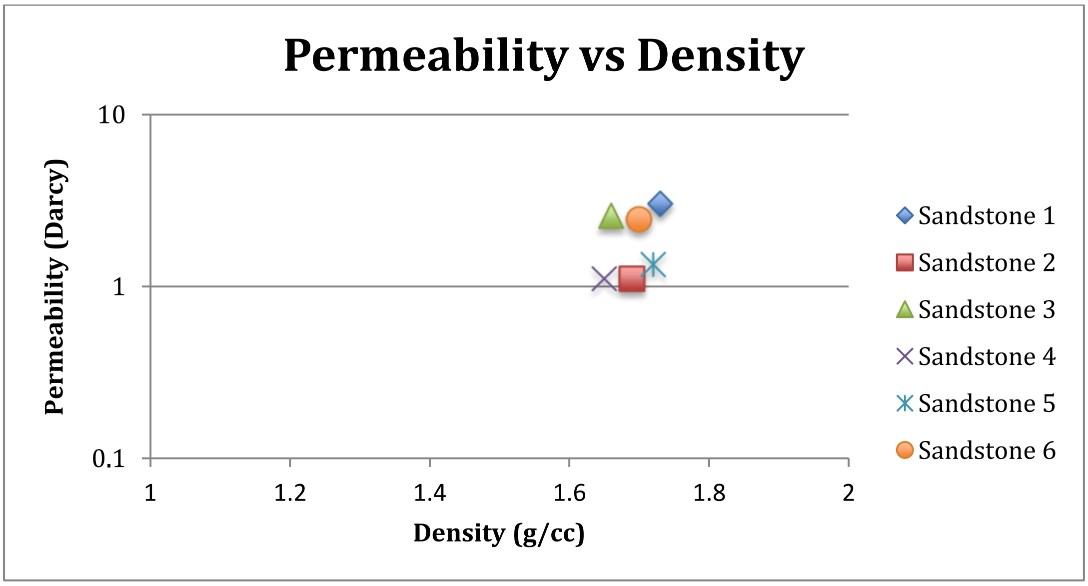

Figure 31 – Cross-plot between permeability and density.

Figure **31** shows cross-plot between permeability and density. Similarly, two groups of sandstone can be deduced from a disperse permeability – density cross-plot. Both groups have low density values, ranging from 1.65 to 1.73g/cc. Samples in group 1 (sandstone 1, sandstone 3, sandstone 6) are characterized by very high permeability (2400-3000 mD) whereas group 2 samples (sandstone 2, sandstone 4, sandstone 5) are of lower permeability (1100 – 1300 mD).

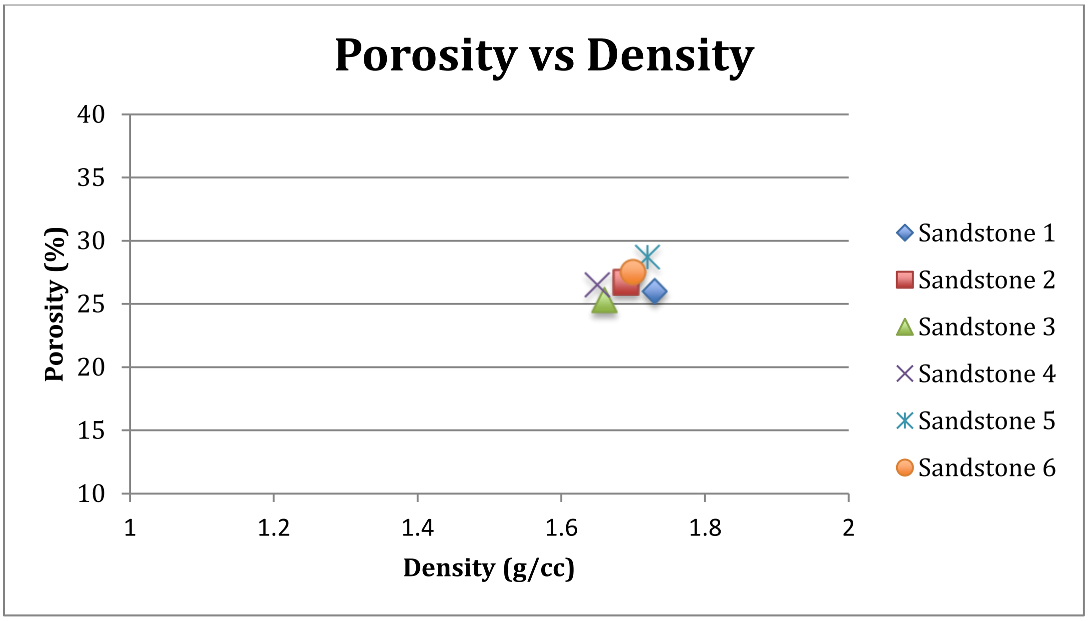

Figure 32 – Cross-plot between porosity acquired from image analysis and density.

The cross-plot in Figure **32** shows a more assembled density and porosity relationship. All the sandstone samples exhibit very high porosity and low density.

4.4. DATA INTEGRATION AND INTERPRETATION

Generally, all six sandstone samples display more or less similar density and porosity values. Therefore, the sandstone group separation shown in permeability – porosity and permeability – density cross-plots is merely due to the difference in permeability. As per interpretation, grouping of samples by permeability is related to the type of permeability measured for the samples, which was also mentioned in Permeability (2010). Those measured with horizontal permeability were recorded as significantly higher values than those measured with vertical permeability due to grains arrangement (Permeability, 2010). Generally, sandstone had porosity ranging from 10 to 30% (Adam, 2009). The samples porosity ranges from 25.3% to 28%, which can be considered as very good porosity to be a reservoir. According to Bear (1972), most oil reservoir rocks have permeability ranges from ten to several hundred millidarcy, one darcy is actually a very high amount of permeability. The permeability recorded in the samples ranges from 1105mD to 3018mD. Therefore, the sandstones of Lambir Formation in Tusan beach display an excellent reservoir rock quality.

4.4.1. Comparison Between Horizontal And Vertical Permeability

Group 1, including Sandstone 1 (Small scale trough cross bedded sandstone), Sandstone 3 (Hummocky cross bedded sandstone), and Sandstone 6 (Trough cross bedded sandstone), is characterized by very high permeability. Group 1 samples are bioturbated at 2 to 4 degree, grain size varies from fine sand to fine silt and well sorted except for Sandstone 6, which is moderately to poorly sorted. Therefore, this could be the reason that Sandstone 6 displays the lowest permeability among the three samples despite the fact that its porosity is the highest in the group (27.5% compared to 26% - Sandstone 1 and 25.3% - Sandstone 3). On the other hand, Sandstone 1 has the best permeability, which is 3018.8mD, regardless of the mud laminations in between cross bed sets. Possible reason for this behavior is that, the sample is well sorted with quartz grains mostly of very fine sand to coarse silt sizes, which are comparatively larger than those in other samples. In Figure 14, the pore throats of Sandstone 1 are observable with large size, allowing for higher gas mobility throughout the core during POROPERM test.

Group 2, which includes Sandstone 2 (Herringbone cross bedded sandstone), Sandstone 4 (Hummocky cross bedded sandstone), and Sandstone 5 (Medium scale trough cross bedded sandstone), shows relatively lower permeability records. Group 2 samples are well sorted, with high bioturbation degree (1 to 3) except for Sandstone 4 (no bioturbation). Among these samples, Sandstone 5 from trough cross-bedded facies presents highest permeability value (1341mD) and highest porosity (28.7%). The large pore throats that can be seen in Figure 18 is a possible contribution to the high permeability measurement of this sample. The other two samples, which are of herringbone cross-bedded sandstone and hummocky cross-bedded sandstone, share the same permeability and porosity values (~1105mD and ~26%) regardless of difference in average grain size (herringbone cross-bedded sandstone has coarser grains).

The ratio between vertical and horizontal permeability (kV/kH) of trough cross-bedded sandstone facies and hummocky cross-bedded sandstone facies are relatively close, ranging from 0.42 to 0.55. This low kV/kH ratio (less than 0.6) is believed to be common in layered or cross-bedded sandstones (Meyer, 2002). Low kV/kH ratio means that the permeability of these facies varies in different direction, indicating high anisotropy. The high permeability anisotropy of layered sandstone is the result of pore network connectivity of the laminae, which is strongly dependent on deposition history of the rock (Meyer, 2002). In case there is no presence of fractures and faults, kV/kH relationship can be a useful indicator to predict vertical permeability of the strata since horizontal permeability is routinely measured (Atmadibrata & Joenoes, 1993).

4.4.2. Comparison Between Sandstone Facies

From the results, we can see that samples belong to trough cross-bedded sandstone facies recorded the highest permeability and porosity values. The three samples belong to this facies are Sandstone 1, Sandstone 5 and Sandstone 6. Observing thin section images of these samples in Figure 14, Figure 18 and Figure 19, it is clearly shown that the mud content in this facies is less than that in the other two facies. This is believed to be the main contribution to the excellent poro-perm result of this facies compared to hummocky and herringbone cross-bedded sandstones.

Grain size also plays an important role in controlling permeability of rocks. Numbers of experiments had been carried out to prove that permeability is proportional to grain diameter (Cade et al., 1994). As grain size increases, pore throat size will increases as well. Subsequently, increase of permeability occurs. Thus, another factor that can lead to high poroperm result in trough cross-bedded sandstones is that average grain size of those samples is fine sand to medium silt whereas in hummocky cross-bedded samples, the quartz grains are mostly silty.

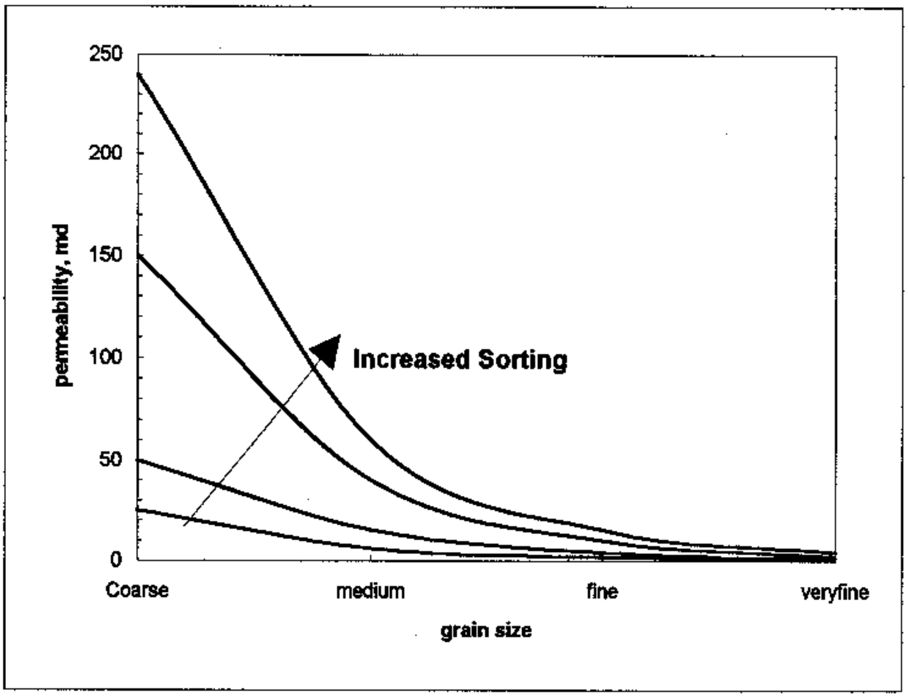

Figure 33 - Effect of grain size and sorting degree on permeability (Permeability, 2010).

Sandstone 5 has the lowest permeability among three samples of trough cross-bedded sandstones. This is believed to be due to the coal laminations that act as obstacles to vertical fluid flow as the permeability measured for this core is vertical permeability. According to outcrop studies, Sandstone 1 sample was taken from trough cross-bed facies with associated mud laminations and Sandstone 6 was taken from trough cross-bed facies with occasional mud drapes. However, for these two cores, the measurement was vertical permeability, therefore, the effects of mud laminations and mud drapes are insignificant. Comparing between Sandstone 1 to Sandstone 6, Sandstone 1 has better sorting degree. This was reflected in permeability results that Sandstone 6 is 500mD less than Sandstone 1.

Hummocky cross-bedded sandstone samples exhibit lower permeability, both horizontal and vertical, compared to trough cross-bedded sandstones. However, in case of Sandstone 6 (trough cross-bedded sandstone), as explained earlier, poor grain sorting is interpreted as the cause for slightly lower horizontal permeability value of this rock (2455mD), compared to Sandstone 3 from hummocky cross-bedded facies (2577mD) (Krumbein & Monk, 1942).

Vertical permeability had been measured for herringbone cross-bedded sandstone (Sandstone 2). The result recorded was 1105.3mD, which is almost equal to that of Sandstone 4 - hummocky cross-bedded sandstone (1105.9mD). Based on grain size distribution histograms of these two samples, herringbone cross-bedded sandstone sample shows average grain size of very fine sand, while hummocky cross-bedded sandstone is of fine silt grains. From this observation, we can predict that hummocky cross-bedded sandstone facies would exhibit higher vertical permeability than herringbone cross-bedded sandstone facies if they are of same level of grain size and grain packing.

Besides, most of the samples are bioturbated at 2 to 4 degree except for Sandstone 4 (Hummocky cross-bedded facies) without any trace of disturbance. Correlation between petrophysical results of the samples and bioturbation degree had not been established, as there is no specific trend showing effect of bioturbation.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

In this project, sedimentology analysis, including facies description of rock strata from Lambir Formation had been done together with petrophysical lab tests and measurements to serve the purpose of establishing the relationship between depositional conditions and reservoir quality. The first part of this project, before going to the field, focuses more on reviewing past researches, works done and methodology. In the second part, field trip had been carried out for the duration of three-week time, during semester break. Based on structural readings, GPS readings and field observations, a map was plotted showing the outcrops and traverse line. Observation shows dominantly sandstone occurs along the traverse line. In total five sandstone facies had been identified: **Facies A:** Massive sandstone; **Facies B.** Trough cross-bedded sandstone; **Facies C.** Herringbone cross-bedded sandstone; **Facies D.** Tabular cross-bedded sandstone; **Facies E.** Hummocky cross-bedded sandstone. Six sandstone samples were taken back for petrophysical test and thin section image analysis. Results show high to very high permeability (1105mD to 3018mD) and very good porosity (25.3% to 28.7%) recorded in all samples, indicating excellent reservoir quality. Observations suggest that horizontal permeability is approximately two times higher than vertical permeability of the same facies. kV/kH ratios in trough cross-bedded and hummocky cross-bedded facies range from 0.42 to 0.55, indicate high permeability anisotropy in these facies. kV/kH ratio obtained from the analysis is important as with available horizontal permeability data, vertical permeability of these strata located offshore can be predicted. Generally, samples belong to trough cross-bedded sandstone facies (sample 1, 5, and 6) recorded highest porosity and permeability values, followed by hummocky cross-bedded sandstones (sample 3 and 4) and lastly, herringbone cross-bedded sandstone (sample 2). Less mud content and coarser grain size in trough cross-bedded samples had contributed to this result. In future work, analysis can be done for rock samples around Lambir hills area. Porosity and permeability values can be compared with rock samples from Tusan beach area to see the differences if there is any. kV/kH ratio of those samples should also be established to examine the kv/kH obtained from the sandstone facies of Tusan beach area.

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APPENDICES.

Figure 34 – Lower section of Outcrop 1.

Figure 35 - Upper section of Outcrop 1.


Figure 36 - A part of Outcrop 2.


Figure 37 - Bioturbated trough cross-bedded sandstones (4 degrees).

Figure 38 - Herringbone cross-bedded sandstone.

Figure 39 - Hummocky cross-bedded sandstone with thin coal lense in between beds.

Figure 40 - Bioturbated trough cross-bedded sandstone with associated mud drapes and coal lense.

Figure 41 - Trough cross-bedded sandstone with coal clast and organic materials fill in between bed sets.